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**PLASMA IMMERSION ION IMPLANTATION PROCESS  
USING A PLASMA SOURCE HAVING  
LOW DISSOCIATION AND LOW MINIMUM PLASMA VOLTAGE**

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CROSS-REFERENCE TO RELATED APPLICATIONS

20 This application is a continuation-in-part of U.S.  
Application Serial No. 10/164,327 filed June 5, 2003 by  
Kenneth Collins et al., entitled EXTERNALLY EXCITED  
TORROIDAL PLASMA SOURCE WITH MAGNETIC CONTROL OF ION  
DISTRIBUTION and assigned to the present assignee.

25  
BACKGROUND OF THE INVENTION

30 The present invention is related to semiconductor  
microelectronic circuit fabrication, and particularly to ion  
implantation using plasma immersion.

35 The formation of semiconductor junctions on the surface  
of a semiconductor crystal (such as silicon wafer) is  
generally carried out by implantation of ions of either  
acceptor or donor impurity species (e.g., Boron or Arsenic)  
into the surface. Currently, ion implantation is  
efficiently carried out by ion beam accelerators. An ion  
beam accelerator raster-scans a beam of donor or acceptor  
ions across the semiconductor wafer surface. The implanted  
40 semiconductor wafer surface is then annealed at elevated  
temperatures in excess of 600 °C in order to cause the

implanted species to be substituted for silicon atoms within the crystal lattice. This process is defined as dopant activation. The depth of the implanted species below the surface, in conjunction with a subsequent anneal process, determines the junction depth, which is determined by the kinetic energy of the ion beam and subsequent annealing thermal budget. The conductance of the implanted region of the semiconductor is determined by the junction depth and the volume concentration of the thermally activated implanted dopant species. The implanted dopant species concentration is controlled by the rate at which the ion beam is scanned across the semiconductor surface and the beam current. The activated implanted dopant species concentration is controlled by the above, and the subsequent anneal process (temperature and time characteristics). For current semiconductor fabrication processes, in which semiconductor circuit feature size is about 130 nm, ion beam accelerators are suitable for ion implantation because the junction depth is fairly deep (over 330 Angstroms) and the required dopant dose is fairly modest (about  $2 \times 10^{14}$  to about  $2 \times 10^{15}$  ions/cm<sup>2</sup>). Such a modest dopant concentration is fulfilled by an ion beam accelerator with an implant operation lasting only minutes. Because of the deep junction depth, the abruptness of the junction need be no smaller than 6 nm/dec (i.e., nanometers per decade of concentration). Therefore, ion energy distribution is not critical, and some ions may have a kinetic energy that carries them somewhat beyond the desired junction depth without degrading the abruptness beyond the 4.1 nm/dec level. Therefore, techniques for enhancing the ion beam flux that compromise ion energy distribution can be used. These techniques include using an ion beam that has a few times the kinetic energy corresponding to the desired junction depth, or about 2 keV, (and therefore several times the ion flux density), and then electrically decelerating the ion beam down to the correct kinetic energy (e.g., 500

eV) just before it impacts the semiconductor wafer surface.

The deceleration process is not precise and leaves a fraction of implanted particles (neutrals) above the correct energy level, which is sometimes referred to as a high energy tail or energy contamination. The high energy tail arises from the natural occurrence of neutrals in the ion beam and the immunity of such neutrals from the electrostatic deceleration process. Such neutrals therefore impact the wafer at the original energy (e.g., 2 keV), so that they are implanted below the desired junction depth, due to the high energy tail, causing a loss of junction abruptness. But this is not harmful because of the relatively relaxed requirement for junction abruptness (6 nm/dec). Moreover, rapid thermal annealing by halogen lamps, for example, tends to "wash out" the effect of the high energy tail due to diffusion.

However, as semiconductor circuit feature size decreases with progress in device speed, ion beam accelerators become less efficient. For example, at a feature size of 65 nm, the junction depth is only about 170 Angstroms and the abruptness is much steeper, at 2.8 nm/dec. With such a shallow junction, the required dopant dose is greater (to avoid an increased resistance), or about  $10^{15}$  to about  $2 \times 10^{16}$  ions/cm<sup>2</sup>. In order to activate such higher dopant concentrations in the silicon crystal, and in order to avoid increasing junction depth during annealing, dynamic surface annealing is advantageously employed, in which the wafer surface (e.g., down to depth of order 1000 Angstroms) is laser-heated to near melting (e.g., 1300 deg. C) for a period of a nanosecond to tens of milliseconds. Dynamic surface annealing activates a higher concentration of dopant and increases junction depth by less than 20 Å compared with rapid thermal annealing. (By comparison, rapid thermal annealing can add over 100 Å to the junction depth, which would double the junction depth in some cases.) However,

dynamic surface annealing does not reduce the high energy tail. Therefore, in order to stay within the more stringent junction abruptness requirement and in order to avoid a high energy tail, the ion beam accelerator must be operated in drift mode, in which the ions are accelerated up to but not beyond the kinetic energy corresponding to the desired junction depth (e.g., only 500 eV), so that no ions will be implanted below the desired depth, and no deceleration process is required. For example, a junction depth of 10-20 nm may translate to an ion beam energy of only 500 eV. Unfortunately, the lower ion energy in drift mode limits the ion beam flux (and current), so that the time required to reach the desired high dopant concentration can be as long as a half hour or one hour. This problem arises particularly in shallow junction implant of light species such as Boron, in which the beam voltage must be reduced to avoid high velocity Boron ions being implanted below the desired junction depth. The problem arises basically because the space charge effects in the ion beam produce repulsive forces between the ions in the beam in a radial direction, generally, limiting the beam density and therefore the beam current. Such effects become more important as the beam energy is reduced (as it must be for implanting the lighter elements such as Boron), resulting in lower beam currents and longer implant times. Such long implant times greatly limit productivity and increase production costs. For example, in order to avoid a decrease in wafer through-put, the number of ion beam implant machines must be increased. In the future, feature sizes will decrease further, down to 45 nm, so that such problems will worsen in proportion as the technology advances.

These problems pertain particularly to cases in which the species to be implanted has a low atomic weight (such as Boron), so that the acceleration voltage must be small, which translates into a small ion beam flux and a long

implant time. For higher atomic weight species (such as Arsenic), the acceleration voltages are much higher and the ion beam flux is therefore sufficiently high to keep implantation times down to an acceptable level. One way of  
5 permitting an increased beam acceleration voltage for lighter implant species such as Boron, in order to improve ion flux and reduce implant time, is to implant molecular ions consisting of one Boron atom or more and another volatile species such as Fluorine, Hydrogen, or other  
10 species. Examples of such molecular ions are  $\text{BF}_2$ ,  $\text{B}_{10}\text{H}_{14}$ . Thus, implanting  $\text{BF}_2$  permits the use of a much higher beam energy and therefore a higher and more acceptable ion beam flux. However, while much of the implanted fluorine tends to diffuse out of the silicon crystal during annealing, a  
15 significant amount does not, leaving some crystal lattice sites that contain neither a semiconductor atom (Si) nor a dopant impurity atom (B), thus (for some applications) reducing the overall quality of the semiconductor material. Therefore, this technique is not desirable universally for  
20 all applications.

In summary, advances in technology dictate a more shallow junction depth, a greater junction abruptness and a higher dopant concentration in the semiconductor surface.  
25 Such advances in technology (where features size decreases to 65 nm and ultimately to 45 nm) render ion beam implantation of lighter dopants such as Boron impractical. This is because the traditional ion beam implanter provides too little ion beam flux in such applications.

30

In order to find an ion source having much higher ion flux for low atomic weight species such as Boron, the field has turned to an ion source whose flux at a given implant depth is less affected by the space charge effect or  
35 (indirectly) atomic weight, namely a plasma ion source. Specifically, the semiconductor wafer is immersed in a

plasma consisting of dopant ions (such as Boron ions). However, such plasma ion immersion implantation has been plagued by various difficulties.

5           One type of plasma immersion ion implantation reactor employs a pulsed D.C. voltage applied to a pedestal supporting the semiconductor wafer in a vacuum chamber filled with a dopant-containing gas such as BF<sub>3</sub>. The D.C. voltage creates a plasma discharge in the chamber in which  
10 Boron ions and other ions dissociated from the BF<sub>3</sub> ions are accelerated into the wafer surface. The D.C. voltage maintains the plasma by creation of secondary electrons from collisions with the chamber surfaces or wafer surface. The rate at which such collisions produce secondary electrons  
15 depends upon the condition of the chamber surfaces. Accordingly, such a reactor is unacceptably sensitive to changes in the condition of the chamber surfaces due, for example, to contamination of the chamber surfaces. As a result, such a plasma ion immersion implantation reactor  
20 cannot maintain a target junction depth or abruptness, for example, and is plagued by contamination problems.

          This type of reactor tends to produce a relatively low density plasma and must be operated at relatively high  
25 chamber pressure in order to maintain the plasma density. The high chamber pressure and the lower plasma density dictate a thicker plasma sheath with more collisions in the sheath that spread out ion energy distribution. This spreading can result in a larger lateral junction  
30 distribution and may reduce junction abruptness. Furthermore, the reactor is sensitive to conditions on the wafer backside because the plasma discharge depends upon ohmic contact between the wafer backside and the wafer support pedestal.

35

          One problem inherent with D.C. voltage applied to the

wafer support is that its pulse width must be such that the dopant ions (e.g., Boron) are accelerated across the plasma sheath near the wafer surface with sufficient energy to reach the desired junction depth below the surface, while  
5 the pulse width must be limited to avoid (discharge) any charge build-up on the wafer surface that would cause device damage (charging damage). The limited pulse width is problematic in that the periodic decrease in ion energy can result in deposition on the semiconductor surface rather  
10 than implantation, the deposition accumulating in a new layer that can block implantation during the pulse on times. Another problem arises because ions must impact the wafer surface with at least a certain target energy in order to penetrate the surface up to a desirable depth (the as-  
15 implanted junction depth) and become substitutional below the surface and up to the desired annealed junction depth during the annealing process. Below this energy, they do not penetrate the surface up to the as-implanted junction depth and do not become substitutional at the desired  
20 junction depth upon annealing. Moreover, the ions below the target energy may simply be deposited on the wafer surface, rather than being implanted, to produce a film that can impede implantation. Unfortunately, due to resistive and capacitive charging effects (RC time constant) on dielectric  
25 films on the wafer that tend to accompany a D.C. discharge, the ions reach the target energy during only a fraction of each pulse period (e.g., during the first microsecond), so that there is an inherent inefficiency. Moreover, the resulting spread in ion energy reduces the abruptness of the  
30 P-N junction. This problem cannot be solved by simply increasing the bias voltage, since this would increase the junction depth beyond the desired junction depth.

Another type of plasma immersion ion implantation  
35 reactor employs inductive coupling to generate the plasma, in addition to the pulsed D.C. voltage on the wafer. This

type of reactor reduces the problems associated with plasma maintenance from secondary electrons, but still suffers from the problems associated with pulsed D.C. voltages on the wafer discussed immediately above.

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Another type of plasma ion immersion implantation reactor employs an RF voltage applied to the wafer support pedestal that both controls ion energy and maintains the plasma. As in the pulsed D.C. voltage discussed above, the RF voltage on the wafer support creates a plasma discharge in the chamber in which Boron ions and other ions dissociated from the  $\text{BF}_3$  ions are accelerated into the wafer surface. The RF voltage generates and maintains the plasma mainly by capacitively coupling RF energy from the electrode across the sheath to electrons in the plasma just above the sheath (low pressure case) or electrons in the bulk plasma volume (high pressure case). While such a reactor has reduced sensitivity to chamber surface conditions as compared to reactors employing a pulsed DC bias, it is still quite sensitive. Also, ion energy and flux cannot be independently selected with a single RF power source. Ion flux may still be unacceptably low for high throughput applications with a single RF power source. Contamination due to wall sputtering or etching may also be high due to elevated plasma potential.

Another type of plasma ion immersion implantation reactor employs a microwave power applicator for generating the plasma. This reactor has a microwave waveguide pointed axially downward to a magnetic field centered about the axis. Electron cyclotron resonance (ECR) occurs in a particular surface of the field to produce the plasma (for a microwave frequency of 2.45 GHz, this surface is where the magnetic field is about 875 gauss). The magnetic field is divergent, with a field gradient creating a drift current towards the substrate being processed. This drift current



consists of both electrons (directly acted on by the interaction of microwave induced electric field and divergent DC magnetic field) and positively-charged ions (indirectly acted on by the deficit in negative charge  
5 formed due to the out-flux of electrons) and corresponding to a voltage of 10 to 100 eV. One problem is that the magnetic field gradient is non-uniform, so that the radial distribution of plasma ion energy is non-uniform, causing non-uniform junction depths across the wafer. Another  
10 problem is the relatively high ion energy directed at the wafer, limiting the degree to which junction depths can be minimized. One way of addressing the non-uniformity issue is to place the microwave ECR source far above the wafer. The problem with such an approach is that the ion density  
15 and flux is at least proportionately decreased, thus reducing the productivity of the reactor. A related problem is that, because the plasma ion density at the wafer surface is reduced by the increased source-to-wafer distance, the chamber pressure must be reduced in order to reduce  
20 recombination losses. This rules out some applications that would be advantageously carried out at high pressure (applications which benefit from wide angular ion energy distribution) such as conformal doping of polysilicon lines and three dimensional devices. Another way of addressing the  
25 non-uniformity issue is to place another magnet array between the source and the wafer, in an effort to straighten the magnetic field. However, the additional magnetic field would increase magnetic flux at the wafer surface, increasing the risk of charge damage to semiconductor  
30 structures on the wafer.

In summary, plasma immersion ion implantation reactors have various limitations, depending upon the type of reactor: plasma reactors in which a pulsed D.C. voltage is  
35 applied to the wafer pedestal are too sensitive to chamber conditions and are inefficient; and plasma reactors with

microwave ECR sources tend to produce non-uniform results. Thus, there is a need for a plasma immersion ion implantation reactor that is free of the foregoing limitations.

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#### SUMMARY OF THE INVENTION

A method for ion implanting a species into a surface layer of a workpiece in a chamber includes placing the workpiece in a processing zone of the chamber bounded by a chamber side wall and a chamber ceiling facing said workpiece and between a pair of ports of the chamber near generally opposite sides to the processing zone and connected together by a conduit external of the chamber. The method further includes introducing into the chamber a process gas comprising the species to be implanted, and further generating from the process gas a plasma current and causing the plasma current to oscillate in a circulatory reentrant path comprising the conduit and the processing zone.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a first case that maintains an overhead torroidal plasma current path.

FIG. 2 is a side view of a case corresponding to the case of FIG. 1.

FIG. 3 is a graph illustrating the behavior of free fluorine concentration in the plasma with variations in wafer-to-ceiling gap distance.

FIG. 4 is a graph illustrating the behavior of free fluorine concentration in the plasma with variations in RF bias power applied to the workpiece.

FIG. 5 is a graph illustrating the behavior of free fluorine concentration in the plasma with variations in RF source power applied to the coil antenna.

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FIG. 6 is a graph illustrating the behavior of free fluorine concentration in the plasma with variations in reactor chamber pressure.

10        FIG. 7 is a graph illustrating the behavior of free fluorine concentration in the plasma with variations in partial pressure of an inert diluent gas such as Argon.

15        FIG. 8 is a graph illustrating the degree of dissociation of process gas as a function of source power for an inductively coupled reactor and for a reactor according to an embodiment of the present invention.

20        FIG. 9 illustrates a variation of the case of FIG. 1.

FIGS. 10 and 11 illustrate a variation of the case of FIG. 1 in which a closed magnetic core is employed.

25        FIG. 12 illustrates another case of the invention in which a torroidal plasma current path passes beneath the reactor chamber.

30        FIG. 13 illustrates a variation of the case of FIG. 10 in which plasma source power is applied to a coil wound around a distal portion the closed magnetic core.

FIG. 14 illustrates a case that establishes two parallel torroidal plasma currents.

35        FIG. 15 illustrates a case that establishes a plurality of individually controlled parallel torroidal plasma

currents.

FIG. 16 illustrates a variation of the case of FIG. 15 in which the parallel torroidal plasma currents enter and exit the plasma chamber through the vertical side wall rather than the ceiling.

FIG. 17A illustrates a case that maintains a pair of mutually orthogonal torroidal plasma currents across the surface of the workpiece.

FIG. 17B illustrates the use of plural radial vanes in the case of FIG. 17A.

FIGS. 18 and 19 illustrate an case of the invention in which the torroidal plasma current is a broad belt that extends across a wide path suitable for processing large wafers.

FIG. 20 illustrates a variation of the case of FIG. 18 in which an external section of the torroidal plasma current path is constricted.

FIG. 21 illustrates a variation of the case of FIG. 18 employing cylindrical magnetic cores whose axial positions may be adjusted to adjust ion density distribution across the wafer surface.

FIG. 22 illustrates a variation of FIG. 21 in which a pair of windings are wound around a pair of groups of cylindrical magnetic cores.

FIG. 23 illustrates a variation of FIG. 22 in which a single common winding is wound around both groups of cores.

FIG. 24 and 25 illustrate an case that maintains a pair

of mutually orthogonal torroidal plasma currents which are wide belts suitable for processing large wafers.

FIG. 26 illustrates a variation of the case of FIG. 25  
5 in which magnetic cores are employed to enhance inductive coupling.

FIG. 27 illustrates a modification of the case of FIG. 24 in which the orthogonal plasma belts enter and exit the  
10 reactor chamber through the vertical side wall rather than through the horizontal ceiling.

FIG. 28A illustrates an implementation of the case of FIG. 24 which produces a rotating torroidal plasma current.  
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FIG. 28B illustrates a version of the case of FIG. 28A that includes magnetic cores.

FIG. 29 illustrates a preferred case of the invention  
20 in which a continuous circular plenum is provided to enclose the torroidal plasma current.

FIG. 30 is a top sectional view corresponding to FIG. 29.  
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FIGS. 31A and 31B are front and side sectional views corresponding to FIG. 30.

FIG. 32 illustrates a variation of the case 29  
30 employing three independently driven RF coils underneath the continuous plenum facing at 120-degree intervals.

FIG. 33 illustrates a variation of the case of FIG. 32 in which the three RF coils are driven at 120-degree phase  
35 to provide an azimuthally rotating plasma.

FIG. 34 illustrates a variation of the case of FIG. 33 in which RF drive coils are wound around vertical external ends of respective magnetic cores whose opposite ends extend horizontally under the plenum at symmetrically distributed angles.

FIG. 35 is a version of the case of FIG. 17 in which the mutually transverse hollow conduits are narrowed as in the case of FIG. 20.

FIG. 36 is a version of the case of FIG. 24 but employing a pair of magnetic cores 3610, 3620 with respective windings 3630, 3640 therearound for connection to respective RF power sources.

FIG. 37 is a case corresponding to that of FIG. 35 but having three instead of two reentrant conduits with a total of six reentrant ports to the chamber.

FIG. 38 is a case corresponding to that of FIG. 38 but having three instead of two reentrant conduits with a total of six reentrant ports to the chamber.

FIG. 39 is a case corresponding to that of FIG. 35 in which the external conduits join together in a common plenum 3910.

FIG. 40 is a case corresponding to that of FIG. 36 in which the external conduits join together in a common plenum 4010.

FIG. 41 is a case corresponding to that of FIG. 37 in which the external conduits join together in a common plenum 4110.

FIG. 42 is a case corresponding to that of FIG. 38 in

which the external conduits join together in a common plenum  
4210.

FIG. 43 is a case corresponding to that of FIG. 17 in  
5 which the external conduits join together in a common plenum  
4310.

FIG. 44 illustrates cases a reactor similar to that of  
FIG. 1 and having a magnetic pole piece for controlling  
10 plasma ion density uniformity.

FIG. 45 illustrates a reactor like that of FIG. 44 in  
which the magnetic pole piece has a reduced diameter near  
the ceiling surface, and the ceiling is a dual zone gas  
15 distribution plate.

FIGS. 46, 47 and 48 illustrate different shapes for the  
pole piece.

20 FIG. 49 illustrates one implementation of the gas  
distribution plate.

FIG. 50 is a detailed view of a gas injection orifice  
in FIG. 49.  
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FIG. 51 is a graph depicting the magnetic field that  
the magnetic pole piece can generate.

FIG. 52 is a graph of the magnetic field magnitude as a  
30 function of radius.

FIGS. 53 and 54 illustrate different ways of  
controlling process gas flow.

35 FIGS. 55A and 55B illustrate the use of a splitter in  
the torroidal plasma path.

FIGS. 56A, 56B and 56C illustrate use of splitters where the torroidal plasma current enters the chamber vertically.

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FIGS. 57 and 58 illustrate different shapes for a splitter.

FIGS. 59A and 59B illustrate use of splitters where the  
10 torroidal plasma current enters the chamber radially.

FIGS. 60, 61, 62 and 63 illustrate the use of splitters where the torroidal plasma current is introduced vertically at a corner of the chamber.

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FIG. 64 illustrates how a splitter may extend only part of the process region height.

FIGS. 65A, 65B and 66 illustrate a splitter design  
20 adapted to increase the effective radial path length of the torroidal plasma current inside the chamber for a given chamber diameter.

FIG. 67 illustrates the use of MERIE magnets with the  
25 torroidal plasma current source of FIG. 1.

FIGS. 68 and 69 illustrate the use of fins to better confine the torroidal plasma current to the processing region.

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FIGS. 70, 71 and 72 illustrate an RF power applicator having distributed inductances.

FIG. 72 illustrates distributed inductances  
35 corresponding to the FIGS. 70, 71A and 71B.



FIG. 73 illustrates a circular arrangement of the distributed inductances of FIG. 72.

FIG. 74 illustrates distributed inductances and  
5 capacitances in an arrangement corresponding to that of  
FIGS. 71A and 71B.

FIGS. 75 and 76 are schematic diagrams illustrating  
different ways of inductively coupling RF power using the  
10 magnetic core of FIGS. 71A and 71B.

FIG. 77 illustrates the use of an insulator layer to  
electrically isolate the termination sections and torroidal  
tubes of FIG. 44.

15 FIG. 78 illustrates how the uniformity control magnet  
or magnetic pole may be placed under the wafer support  
pedestal.

20 FIG. 79 depicts an inductively coupled plasma immersion  
ion implantation reactor having an RF bias power applicator.

FIGS. 80A, 80B and 80C illustrate, respectively, an  
applied pulsed D.C. bias voltage, the corresponding sheath  
25 voltage behavior and an applied RF bias voltage.

FIGS. 81A, 81B, 81C and 81D illustrate, respectively,  
an energy distribution of ion flux, a cycle of applied RF  
bias voltage, ion saturation current as a function of D.C.  
30 bias voltage, and energy distribution of ion flux for  
different frequencies of RF bias voltage.

FIGS. 82A and 82B illustrate the temporal relationship  
between the power output waveforms of the source power  
35 generator and the bias power generator in a push-pull mode.

FIGS. 82C and 82D illustrate the temporal relationship between the power output waveforms of the source power generator and the bias power generator in an in-synchronism mode.

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FIGS. 82E and 82F illustrate the temporal relationship between the power output waveforms of the source power generator and the bias power generator in a symmetric mode.

10        FIGS. 82G and 82H illustrate the temporal relationship between the power output waveforms of the source power generator and the bias power generator in a non-symmetric mode.

15        FIGS. 83A and 83B illustrate different versions of a capacitively coupled plasma immersion ion implantation reactor having an RF bias power applicator.

20        FIG. 84 illustrates a plasma immersion ion implantation reactor having a reentrant torroidal path plasma source.

25        FIG. 85 illustrates a plasma immersion ion implantation reactor having a torroidal plasma source with two intersecting reentrant plasma paths.

25

FIG. 86 illustrates an interior surface of the ceiling of the reactor of FIG. 85.

30        FIG. 87 illustrates a gas distribution panel of the reactor of FIG. 85.

FIG. 88 is a partial view of the reactor of FIG. 85 modified to include a plasma control center electromagnet.

35        FIGS. 89A and 89B are side and top views, respectively, of a version of the reactor of FIG. 88 having, in addition,

a plasma control outer electromagnet.

FIGS. 90A, 90B and 90C are cross-sectional side view of  
the outer electromagnet of FIG. 89A with different gap  
5 distances of a bottom plate for regulating magnetic flux.

FIG. 91 illustrates an RF bias power coupling circuit  
in the reactor of FIG. 85.

10 FIG. 92 depicts an RF bias voltage waveform in  
accordance with a bias voltage control feature.

FIG. 93 is a block diagram illustrating a control  
system for controlling bias voltage in accordance with the  
15 feature illustrated in FIG. 92.

FIG. 94 is a top view of a vacuum control valve  
employed in the reactor of FIG. 85.

20 FIG. 95 is a cross-sectional side view of the valve of  
FIG. 94 in the closed position.

FIG. 96 is a side view of the interior surface of the  
housing of the valve of FIG. 95 with an orientation at right  
25 angles to that of FIG. 95.

FIG. 97 is a cross-sectional side view of a high  
voltage wafer support pedestal useful in the reactor of FIG.  
85.

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FIG. 98 is an enlarged cross-sectional view of the  
wafer support pedestal of FIG. 97 illustrating a fastener  
therein.

35 FIG. 99 is a block diagram illustrating an ion  
implantation processing system including a plasma immersion

ion implantation reactor.

FIG. 100 is a graph illustrating electron density as a function of applied plasma source power for the inductively coupled plasma immersion ion implantation reactor of FIG. 79 and the torroidal source plasma immersion ion implantation reactor of FIG. 85.

FIG. 101 is a graph illustrating free fluorine density as a function of applied plasma source power for the inductively coupled plasma immersion ion implantation reactor of FIG. 79 and the torroidal source plasma immersion ion implantation reactor of FIG. 85.

FIG. 102 is a graph illustrating electron density as a function of applied plasma source power for the capacitively coupled plasma immersion ion implantation reactor of FIG. 83A and the torroidal source plasma immersion ion implantation reactor of FIG. 85.

FIG. 103 is a graph illustrating dopant concentration as a function of junction depth for different ion energies in the reactor of FIG. 85 and in a convention ion beam implant machine.

FIG. 104 is a graph illustrating dopant concentration before and after post-implant rapid thermal annealing.

FIG. 105 is a graph illustrating dopant concentration before and after dynamic surface annealing in the torroidal source plasma immersion ion implantation reactor of FIG. 85 and in a convention ion beam implant machine.

FIG. 106 is a graph depicting wafer resistivity after ion implantation and annealing as a function of junction depth obtained with the reactor of FIG. 85 using dynamic

surface annealing and with a conventional ion beam implant machine using rapid thermal annealing.

FIG. 107 is a graph depicting implanted dopant  
5 concentration obtained with the reactor of FIG. 85 before and after dynamic surface annealing.

FIG. 108 is a graph of RF bias voltage in the reactor  
of FIG. 85 (left ordinate) and of beamline voltage in a  
10 beamline implant machine (right ordinate) as a function of junction depth.

FIG. 109 is a cross-sectional view of the surface of a wafer during ion implantation of source and drain contacts  
15 and of the polysilicon gate of a transistor.

FIG. 110 is a cross-sectional view of the surface of a wafer during ion implantation of the source and drain extensions of a transistor.

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FIG. 111 is a flow diagram illustrating an ion implantation process carried out using the reactor of FIG. 85.

FIG. 112 is a flow diagram illustrating a sequence of possible pre-implant, ion implant and possible post implant processes carried using the reactor of FIG. 85 in the system of FIG. 99.

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#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS Description of a Torroidal Source Reactor:

Referring to FIG. 1, a plasma reactor chamber 100 enclosed by a cylindrical side wall 105 and a ceiling 110  
35 houses a wafer pedestal 115 for supporting a semiconductor wafer or workpiece 120. A process gas supply 125 furnishes

process gas into the chamber 100 through gas inlet nozzles 130a-130d extending through the side wall 105. A vacuum pump 135 controls the pressure within the chamber 100, typically holding the pressure below 0.5 milliTorrr (mT). A  
5 half-torroidal hollow tube enclosure or conduit 150 extends above the ceiling 110 in a half circle. The conduit 150, although extending externally outwardly from ceiling 110, is nevertheless part of the reactor and forms a wall of the chamber. Internally it shares the same evacuated atmosphere  
10 as exists elsewhere in the reactor. In fact, the vacuum pump 135, instead of being coupled to the bottom of the main part of the chamber as illustrated in FIG. 1, may instead be coupled to the conduit 150. The conduit 150 has one open end 150a sealed around a first opening 155 in the reactor  
15 ceiling 110 and its other end 150b sealed around a second opening 160 in the reactor ceiling 110. The two openings or ports 150, 160 are located on generally opposite sides of the wafer support pedestal 115. The hollow conduit 150 is reentrant in that it provides a flow path which exits the  
20 main portion of the chamber at one opening and re-enters at the other opening. In this specification, the conduit 150 may be described as being half-torroidal, in that the conduit is hollow and provides a portion of a closed path in which plasma may flow, the entire path being completed by  
25 flowing across the entire process region overlying the wafer support pedestal 115. Notwithstanding the use of the term **torroidal**, the trajectory of the path as well as the cross-sectional shape of the path or conduit 150 may be circular or non-circular, and may be square, rectangular or any other  
30 shape either a regular shape or irregular.

The external conduit 150 may be formed of a relatively thin conductor such as sheet metal, but sufficiently strong to withstand the vacuum within the chamber. In order to  
35 suppress eddy currents in the sheet metal of the hollow

conduit 150 (and thereby facilitate coupling of an RF inductive field into the interior of the conduit 150), an insulating gap 152 extends across and through the hollow conduit 150 so as to separate it into two tubular sections.

5 The gap 152 is filled by a ring 154 of insulating material such as a ceramic in lieu of the sheet metal skin, so that the gap is vacuum tight. A second insulating gap 153 may be provided, so that one section of the conduit 150 is electrically floating. A bias RF generator 162 applies RF

10 bias power to the wafer pedestal 115 and wafer 120 through an impedance match element 164.

The hollow conduit 150 may be formed of a machined metal, such as aluminum or aluminum alloy. Passages for

15 liquid cooling or heating may be incorporated in the walls of the hollow conduit.

Alternatively, the hollow conduit 150 may be formed of a non-conductive material instead of the conductive sheet

20 metal. The non-conductive material may be a ceramic, for example. In such an alternative case, neither gap 152 or 153 is required.

An antenna 170 such as a winding or coil 165 disposed

25 on one side of the hollow conduit 150 and wound around an axis parallel to the axis of symmetry of the half-torroidal tube is connected through an impedance match element 175 to an RF power source 180. The antenna 170 may further include a second winding 185 disposed on the opposite side of the

30 hollow conduit 150 and wound in the same direction as the first winding 165 so that the magnetic fields from both windings add constructively.

Process gases from the chamber 100 fill the hollow

35 conduit 150. In addition, a separate process gas supply 190 may supply process gases directly in to the hollow conduit

150 through a gas inlet 195. The RF field in the external hollow conduit 150 ionizes the gases in the tube to produce a plasma. The RF field induced by the circular coil antenna 170 is such that the plasma formed in the tube 150 reaches  
5 through the region between the wafer 120 and the ceiling 110 to complete a torroidal path that includes the half-torroidal hollow conduit 150. As employed herein, the term **torroidal** refers to the closed and solid nature of the path, but does not refer or limit its cross-sectional shape or  
10 trajectory, either of which may be circular or non-circular or square or otherwise. Plasma circulates (oscillates) through the complete torroidal path or region which may be thought of as a closed plasma circuit. The torroidal region extends across the diameter of the wafer 120 and, in certain  
15 cases, has a sufficient width in the plane of the wafer so that it overlies the entire wafer surface.

The RF inductive field from the coil antenna 170 includes a magnetic field which itself is closed (as are all  
20 magnetic fields), and therefore induces a plasma current along the closed torroidal path described here. It is believed that power from the RF inductive field is absorbed at generally every location along the closed path, so that plasma ions are generated all along the path. The RF power  
25 absorption and rate of plasma ion generation may vary among different locations along the closed path depending upon a number of factors. However, the current is generally uniform along the closed path length, although the current density may vary. This current alternates at the frequency  
30 of the RF signal applied to the antenna 170. However, since the current induced by the RF magnetic field is closed, the current must be conserved around the circuit of the closed path, so that the amount of current flowing in any portion of the closed path is generally the same as in any other  
35 portion of the path. As will be described below, this fact



is exploited in the invention to great advantage.

The closed torroidal path through which the plasma current flows is bounded by plasma sheaths formed at the various conductive surfaces bounding the path. These conductive surfaces include the sheet metal of the hollow conduit 150, the wafer (and/or the wafer support pedestal) and the ceiling overlying the wafer. The plasma sheaths formed on these conductive surfaces are charge-depleted regions produced as the result of the charge imbalance due to the greater mobility of the low-mass negative electrons and the lesser mobility of the heavy-mass positive ions. Such a plasma sheath has an electric field perpendicular to the local surface underlying the sheath. Thus, the RF plasma current that passes through the process region overlying the wafer is constricted by and passes between the two electric fields perpendicular to the surface of the ceiling facing the wafer and the surface of the wafer facing the gas distribution plate. The thickness of the sheath (with RF bias applied to the workpiece or other electrode) is greater where the electric field is concentrated over a small area, such as the wafer, and is less in other locations such as the sheath covering the ceiling and the large adjoining chamber wall surfaces. Thus, the plasma sheath overlying the wafer is much thicker. The electric fields of the wafer and ceiling/gas distribution plate sheaths are generally parallel to each other and perpendicular to the direction of the RF plasma current flow in the process region.

30

When RF power is first applied to the coil antenna 170, a discharge occurs across the gap 152 to ignite a capacitively coupled plasma from gases within the hollow conduit 150. Above a threshold power level, the discharge and plasma current become spatially continuous through the length of the hollow conduit 150 and along the entire

35

torroidal path. Thereafter, as the plasma current through the hollow conduit 150 increases, the inductive coupling of the RF field becomes more dominant so that the plasma becomes an inductively coupled plasma. Alternatively, 5 plasma may be initiated by other means, such as by RF bias applied to the workpiece support or other electrode or by a spark or ultraviolet light source.

10 In order to avoid edge effects at the wafer periphery, the ports 150, 160 are separated by a distance that exceeds the diameter of the wafer. For example, for a 12 inch diameter wafer, the ports 150, 160 are about 14 to 22 inches apart. For an 8 inch diameter wafer, the ports 150, 160 are about 9 to 16 inches apart.

15 Notwithstanding the use of the term "wafer", the workpiece may be any shape, such as rectangular. The workpiece material may be a semiconductor, insulator, or conductor, or a combination of various materials. The 20 workpiece may have 2-dimensional or 3-dimensional structure, as well.

#### Advantages:

25 A significant advantage is that power from the RF inductive field is absorbed throughout the relatively long closed torroidal path (i.e., long relative to the gap length between the wafer and the reactor ceiling), so that RF power absorption is distributed over a large area. As a result, 30 the RF power density in the vicinity of the wafer-to-ceiling gap (i.e., the process region 121 best shown in FIG. 2, not to be confused with the insulating gap 152) is relatively low, thus reducing the likelihood of device damage from RF fields. In contrast, in prior inductively coupled reactors, 35 all of the RF power is absorbed within the narrow wafer-to-ceiling gap, so that it is greatly concentrated in that

region. Moreover, this fact often limits the ability to narrow the wafer-to-ceiling gap (in the quest of other advantages) or, alternatively, requires greater concentration of RF power in the region of the wafer. Thus, the invention overcomes a limitation of long standing in the art. This aspect enhances process performance for some applications by reducing residency time of the reactive gases through a dramatic reduction in volume of the process region or process zone overlying the wafer, as discussed previously herein.

A related and even more important advantage is that the plasma density at the wafer surface can be dramatically increased without increasing the RF power applied to the coil antenna 170 (leading to greater efficiency). This is accomplished by reducing the cross-sectional area of the torroidal path in the vicinity of the pedestal surface and wafer 120 relative to the remainder of the torroidal path. By so constricting the torroidal path of the plasma current near the wafer only, the density of the plasma near the wafer surface is increased proportionately. This is because the torroidal path plasma current through the hollow conduit 150 must be at least nearly the same as the plasma current through the pedestal-to-ceiling (wafer-to-ceiling) gap.

A significant difference over the prior art is that not only is the RF field remote from the workpiece, and not only can ion density be increased at the wafer surface without increasing the applied RF field, but the plasma ion density and/or the applied RF field may be increased without increasing the minimum wafer-to-ceiling gap length. Formerly, such an increase in plasma density necessitated an increase in the wafer-to-ceiling gap to avoid strong fields at the wafer surface. In contrast, in the present invention the enhanced plasma density is realized without requiring any increase in the wafer-to-ceiling gap to avoid a

concomitant increase in RF magnetic fields at the wafer surface. This is because the RF field is applied remotely from the wafer and moreover need not be increased to realize an increase in plasma density at the wafer surface. As a result, the wafer-to-ceiling gap can be reduced down to a fundamental limit to achieve numerous advantages. For example, if the ceiling surface above the wafer is conductive, then reducing the wafer-to-ceiling gap improves the electrical or ground reference provided by the conductive ceiling surface. A fundamental limit on the minimum wafer-to-ceiling gap length is the sum of the thicknesses of the plasma sheaths on the wafer surface and on the ceiling surface.

A further advantage of the invention is that because the RF inductive field is applied along the entire torroidal path of the RF plasma current (so that its absorption is distributed as discussed above), the chamber ceiling 110, unlike with most other inductively powered reactors, need not function as a window to an inductive field and therefore may be formed of any desired material, such as a highly conductive and thick metal, and therefore may comprise a conductive gas distribution plate as will be described below, for example. As a result, the ceiling 110 readily provides a reliable electric potential or ground reference across the entire plane of the pedestal or wafer 120.

### Increasing the Plasma Ion Density:

One way of realizing higher plasma density near the wafer surface by reducing plasma path cross-sectional area over the wafer is to reduce the wafer-to-ceiling gap length. This may be accomplished by simply reducing the ceiling height or by introducing a conductive gas distribution plate or showerhead over the wafer, as illustrated in FIG. 2. The

gas distribution showerhead 210 of FIG. 2 consists of a gas distribution plenum 220 connected to the gas supply 125 and communicating with the process region over the wafer 120 through plural gas nozzle openings 230. The advantage of the conductive showerhead 210 is two-fold: First, by virtue of its close location to the wafer, it constricts the plasma path over the wafer surface and thereby increases the density of the plasma current in that vicinity. Second, it provides a uniform electrical potential reference or ground plane close to and across the entire wafer surface.

In order to avoid arcing across the openings 230, each opening 230 may be relatively small, on the order of a millimeter (e.g., hole diameter is approximately 0.5 mm). The spacing between adjacent openings may be on the order of a several millimeters.

The conductive showerhead 210 constricts the plasma current path rather than providing a short circuit through itself because a plasma sheath is formed around the portion of the showerhead surface immersed in the plasma. The sheath has a greater impedance to the plasma current than the space between the wafer 120 and the showerhead 210, and therefore virtually all the plasma current goes around the conductive showerhead 210.

It is not necessary to employ a showerhead (e.g., the showerhead 210) in order to constrict the torroidal plasma current or path in the vicinity of the process region overlying the wafer. The path constriction and consequent increase in plasma ion density in the process region may be achieved without the showerhead 210 by similarly reducing the wafer-to-ceiling height. If the showerhead 210 is eliminated in this manner, then the process gases may be supplied into the chamber interior by means of conventional gas inlet nozzles, gas diffusers, or gas slots (not shown).

One advantage of the showerhead 210 is that different mixtures of reactive and inert process gas ratios may be introduced through different orifices 230 at different radii, in order to finely adjust the uniformity of plasma effects on photoresist, for example. Thus, for example, a greater proportion of inert gas to reactive gas may be supplied to the orifices 230 lying outside a median radius while a greater proportion of reactive gas to inert gas may be supplied to the orifices 230 within that median radius.

As will be described below, another way in which the torroidal plasma current path may be constricted in the process region overlying the wafer (in order to increase plasma ion density over the wafer) is to increase the plasma sheath thickness on the wafer by increasing the RF bias power applied to the wafer support pedestal. Since as described previously the plasma current across the process region is confined between the plasma sheath at the wafer surface and the plasma sheath at the ceiling (or showerhead) surface, increasing the plasma sheath thickness at the wafer surface necessarily decreases the cross-section of the portion of the torroidal plasma current within process region, thereby increasing the plasma ion density in the process region. Thus, as will be described more fully later in this specification, as RF bias power on the wafer support pedestal is increased, plasma ion density near the wafer surface is increased accordingly.

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#### High Etch Selectivity at High Etch Rates:

The invention solves the problem of poor etch selectivity which sometimes occurs with a high density plasma. The reactor of FIGS. 1 and 2 has a silicon dioxide-to-photoresist etch selectivity as high as that of a capacitively coupled plasma reactor (about 7:1) while

providing high etch rates approaching that of a high density inductively coupled plasma reactor. It is believed that the reason for this success is that the reactor structure of FIGS. 1 and 2 reduces the degree of dissociation of the reactive process gas, typically a fluorocarbon gas, so as to reduce the incidence of free fluorine in the plasma region over the wafer 120. Thus, the proportion of free fluorine in the plasma relative to other species dissociated from the fluorocarbon gas is desirably reduced. Such other species include the protective carbon-rich polymer precursor species formed in the plasma from the fluorocarbon process gas and deposited on the photoresist as a protective polymer coating. They further include less reactive etchant species such as CF and CF<sub>2</sub> formed in the plasma from the fluorocarbon process gas. Free fluorine tends to attack photoresist and the protective polymer coating formed thereover as vigorously as it attacks silicon dioxide, thus reducing oxide-to-photoresist etch selectivity. On the other hand, the less reactive etch species such as CF<sub>2</sub> or CF tend to attack photoresist and the protective polymer coating formed thereover more slowly and therefore provide superior etch selectivity.

It is believed that the reduction in the dissociation of the plasma species to free fluorine is accomplished in the invention by reducing the residency time of the reactive gas in the plasma. This is because the more complex species initially dissociated in the plasma from the fluorocarbon process gas, such as CF<sub>2</sub> and CF are themselves ultimately dissociated into simpler species including free fluorine, the extent of this final step of dissociation depending upon the residency time of the gas in the plasma. The term "residency time" or "residence time" as employed in this specification corresponds generally to the average time that a process gas molecule and the species dissociated from the that molecule are present in the process region overlying

the workpiece or wafer. This time or duration extends from the initial injection of the molecule into the process region until the molecule and/or its dissociated progeny are pass out of the process region along the closed torroidal path described above that extends through the processing zone.

It is also believed that the reduction in the dissociation of the plasma species to free fluorine is accomplished by reducing the power density of the applied plasma source power as compared to conventional inductively coupled plasma sources. As stated above, power from the RF inductive field is absorbed throughout the relatively long closed torroidal path (i.e., long relative to the gap length between the wafer and the reactor ceiling), so that RF power absorption is distributed over a large area. As a result, the RF power density in the vicinity of the wafer-to-ceiling gap (i.e., the process region 121 best shown in FIG. 2, not to be confused with the insulating gap 152) is relatively low, thus reducing the dissociation of molecular gases.

As stated above, the invention enhances etch selectivity by reducing the residency time in the process region of the fluorocarbon process gas. The reduction in residency time is achieved by constricting the plasma volume between the wafer 120 and the ceiling 110.

The reduction in the wafer-to-ceiling gap or volume has certain beneficial effects. First, it increases plasma density over the wafer, enhancing etch rate. Second, residency time falls as the volume is decreased. As referred to above, the small volume is made possible in the present invention because, unlike conventional inductively coupled reactors, the RF source power is not deposited within the confines of the process region overlying the wafer but rather power deposition is distributed along the



entire closed torroidal path of the plasma current.  
Therefore, the wafer-to-ceiling gap can be less than a skin  
depth of the RF inductive field, and in fact can be so small  
as to significantly reduce the residency time of the  
5 reactive gases introduced into the process region, a  
significant advantage.

There are two ways of reducing the plasma path cross-  
section and therefore the volume over the wafer 120. One is  
10 to reduce the wafer-to-showerhead gap distance. The other  
is to increase the plasma sheath thickness over the wafer by  
increasing the bias RF power applied to the wafer pedestal  
115 by the RF bias power generator 162, as briefly mentioned  
above. Either method results in a reduction in free  
15 fluorine content of the plasma in the vicinity of the wafer  
120 (and consequent increase in dielectric-to-photoresist  
etch selectivity) as observed using optical emission  
spectroscopy (OES) techniques.

20 There are three additional methods of the invention for  
reducing free fluorine content to improve etch selectivity.  
One method is to introduce a non-chemically reactive diluent  
gas such as argon into the plasma. The argon gas may be  
introduced outside and above the process region by injecting  
25 it directly into the hollow conduit 150 from the second  
process gas supply 190, while the chemically reactive  
process gases (fluorocarbon gases) enter the chamber only  
through the showerhead 210. With this advantageous  
arrangement, the argon ions, neutrals, and excited neutrals  
30 propagate within the torroidal path plasma current and  
through the process region across the wafer surface to  
dilute the newly introduced reactive (e.g., fluorocarbon)  
gases and thereby effectively reduce their residency time  
over the wafer. Another method of reducing plasma free  
35 fluorine content is to reduce the chamber pressure. A  
further method is to reduce the RF source power applied to

the coil antenna 170.

FIG. 3 is a graph illustrating a trend observed in the invention in which the free fluorine content of the plasma decreases as the wafer-to-showerhead gap distance is decreased. FIG. 4 is a graph illustrating that the free fluorine content of the plasma is decreased by decreasing the plasma bias power applied to the wafer pedestal 115. FIG. 5 is a graph illustrating that plasma free fluorine content is reduced by reducing the RF source power applied to the coil antenna 170. FIG. 6 is a graph illustrating that the free fluorine content is reduced by reducing chamber pressure. FIG. 7 is a graph illustrating that plasma free fluorine content is reduced by increasing the diluent (Argon gas) flow rate into the tubular enclosure 150. The graphs of FIGS. 3-7 are merely illustrative of plasma behavioral trends inferred from numerous OES observations and do not depict actual data.

#### Wide Process Window:

The chamber pressure is generally less than 0.5 T and can be as low as 1 mT. The process gas may be  $C_4F_8$  injected into the chamber 100 through the gas distribution showerhead at a flow rate of about 15 cc/m with 150 cc/m of Argon, with the chamber pressure being maintained at about 20 mT. Alternatively, the Argon gas flow rate may be increased to 650 cc/m and the chamber pressure to 60 mT. The antenna 170 may be excited with about 500 Watts of RF power at 13 MHz. The wafer-to-showerhead gap may be about 0.3 inches to 2 inches. The bias RF power applied to the wafer pedestal may be 13 MHz at 2000 Watts. Other selections of frequency may be made. The source power applied to the coil antenna 170 may be as low as 50 kHz or as high as several times 13 MHz or higher. The same is true of the bias power applied to the wafer pedestal.

The process window for the reactor of FIGS. 1 and 2 is far wider than the process window for a conventional inductively coupled reactor. This is illustrated in the graph of FIG. 8, showing the specific neutral flux of free fluorine as a function of RF source power for a conventional inductive reactor and for the reactor of FIGS. 1 and 2. For the conventional inductively coupled reactor, FIG. 8 shows that the free fluorine specific flux begins to rapidly increase as the source power exceeds between 50 and 100 Watts. In contrast, the reactor of FIGS. 1 and 2 can accept source power levels approaching 1000 Watts before the free fluorine specific flux begins to increase rapidly. Therefore, the source power process window in the invention is nearly an order of magnitude wider than that of a conventional inductively coupled reactor, a significant advantage.

#### Dual Advantages:

The constriction of the torroidal plasma current path in the vicinity of the wafer or workpiece produces two independent advantages without any significant tradeoffs of other performance criteria: (1) the plasma density over the wafer is increased without requiring any increase in plasma source power, and (2) the etch selectivity to photoresist or other materials is increased, as explained above. It is believed that in prior plasma reactors it has been impractical if not impossible to increase the plasma ion density by the same step that increases etch selectivity. Thus, the dual advantages realized with the torroidal plasma source of the present invention appear to be a revolutionary departure from the prior art.

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#### Other Embodiments:

FIG. 9 illustrates a modification of the case of FIG. 1 in which the side antenna 170 is replaced by a smaller antenna 910 that fits inside the empty space between the ceiling 110 and the hollow conduit 150. The antenna 910 is a single coil winding centered with respect to the hollow conduit 150.

FIGS. 10 and 11 illustrate how the case of FIG. 1 may be enhanced by the addition of a closed magnetically permeable core 1015 that extends through the space between the ceiling 110 and the hollow conduit 150. The core 1015 improves the inductive coupling from the antenna 170 to the plasma inside the hollow conduit 150.

Impedance match may be achieved without the impedance match circuit 175 by using, instead, a secondary winding 1120 around the core 1015 connected across a tuning capacitor 1130. The capacitance of the tuning capacitor 1130 is selected to resonate the secondary winding 1120 at the frequency of the RF power source 180. For a fixed tuning capacitor 1130, dynamic impedance matching may be provided by frequency tuning and/or by forward power servoing.

FIG. 12 illustrates a case of the invention in which a hollow tube enclosure 1250 extends around the bottom of the reactor and communicates with the interior of the chamber through a pair of openings 1260, 1265 in the bottom floor of the chamber. A coil antenna 1270 follows along side the torroidal path provided by the hollow tube enclosure 1250 in the manner of the case of FIG. 1. While FIG. 12 shows the vacuum pump 135 coupled to the bottom of the main chamber, it may just as well be coupled instead to the underlying conduit 1250.

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FIG. 13 illustrates a variation of the case of FIGS. 10

and 11, in which the antenna 170 is replaced by an inductive winding 1320 surrounding an upper section of the core 1015. Conveniently, the winding 1320 surrounds a section of the core 1015 that is above the conduit 150 (rather than below it). However, the winding 1320 can surround any section of the core 1015.

FIG. 14 illustrates an extension of the concept of FIG. 13 in which a second hollow tube enclosure 1450 runs parallel to the first hollow conduit 150 and provides a parallel torroidal path for a second torroidal plasma current. The tube enclosure 1450 communicates with the chamber interior at each of its ends through respective openings in the ceiling 110. A magnetic core 1470 extends under both tube enclosures 150, 1450 and through the coil antenna 170.

FIG. 15 illustrates an extension of the concept of FIG. 14 in which an array of parallel hollow tube enclosures 1250a, 1250b, 1250c, 1250d provide plural torroidal plasma current paths through the reactor chamber. In the case of FIG. 15, the plasma ion density is controlled independently in each individual hollow conduit 1250a-d by an individual coil antenna 170a-d, respectively, driven by an independent RF power source 180a-d, respectively. Individual cylindrical open cores 1520a-1520d may be separately inserted within the respective coil antennas 170a-d. In this case, the relative center-to-edge ion density distribution may be adjusted by separately adjusting the power levels of the individual RF power sources 180a-d.

FIG. 16 illustrates a modification of the case of FIG. 15 in which the array of tube enclosures 1250a-d extend through the side wall of the reactor rather than through the ceiling 110. Another modification illustrated in FIG. 16 is the use of a single common magnetic core 1470 adjacent all

of the tube enclosures 1250a-d and having the antenna 170 wrapped around it so that a single RF source excites the plasma in all of the tube enclosures 1250a-d.

5           FIG. 17A illustrates a pair of orthogonal tube enclosures 150-1 and 150-2 extending through respective ports in the ceiling 110 and excited by respective coil antennas 170-1 and 170-2. Individual cores 1015-1 and 1015-2 are within the respective coil antennas 170-1 and 170-2.  
10 This case creates two mutually orthogonal torroidal plasma current paths over the wafer 120 for enhanced uniformity. The two orthogonal torroidal or closed paths are separate and independently powered as illustrated, but intersect in the process region overlying the wafer, and otherwise do not  
15 interact. In order to assure separate control of the plasma source power applied to each one of the orthogonal paths, the frequency of the respective RF generators 180a, 180b of FIG. 17 are different, so that the operation of the impedance match circuits 175a, 175b is decoupled. For  
20 example, the RF generator 180a may produce an RF signal at 11 MHz while the RF generator 180b may produce an RF signal at 12 MHz. Alternatively, independent operation may be achieved by offsetting the phases of the two RF generators 180a, 180b.

25           FIG. 17B illustrates how radial vanes 181 may be employed to guide the torroidal plasma currents of each of the two conduits 150-1, 150-2 through the processing region overlying the wafer support. The radial vanes 181 extend  
30 between the openings of each conduit near the sides of the chamber up to the edge of the wafer support. The radial vanes 181 prevent diversion of plasma from one torroidal path to the other torroidal path, so that the two plasma currents only intersect within the processing region  
35 overlying the wafer support.

Cases Suitable for Large Diameter Wafers:

In addition to the recent industry trends toward smaller device sizes and higher device densities, another trend is toward greater wafer diameters. For example, 12-inch diameter wafers are currently entering production, and perhaps larger diameter wafers will be in the future. The advantage is greater throughput because of the large number of integrated circuit die per wafer. The disadvantage is that in plasma processing it is more difficult to maintain a uniform plasma across a large diameter wafer. The following cases of the present invention are particularly adapted for providing a uniform plasma ion density distribution across the entire surface of a large diameter wafer, such as a 12-inch diameter wafer.

FIGS. 18 and 19 illustrate a hollow tube enclosure 1810 which is a wide flattened rectangular version 1850 of the hollow conduit 150 of FIG. 1 that includes an insulating gap 1852. This version produces a wide "belt" of plasma that is better suited for uniformly covering a large diameter wafer such as a 12-inch diameter wafer or workpiece. The width W of the tube enclosure and of the pair of openings 1860, 1862 in the ceiling 110 may exceed the wafer by about 5% or more. For example, if the wafer diameter is 10 inches, then the width W of the rectangular tube enclosure 1850 and of the openings 1860, 1862 is about 11 inches. FIG. 20 illustrates a modified version 1850' of the rectangular tube enclosure 1850 of FIGS. 18 and 19 in which a portion 1864 of the exterior tube enclosure 1850 is constricted.

FIG. 20 further illustrates the optional use of focusing magnets 1870 at the transitions between the constricted and unconstricted portions of the enclosure 1850. The focusing magnets 1870 promote a better movement of the plasma between the constricted and unconstricted

portions of the enclosure 1850, and specifically promote a more uniform spreading out of the plasma as it moves across the transition between the constricted portion 1864 and the unconstricted portion of the tube enclosure 1850.

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FIG. 21 illustrates how plural cylindrical magnetic cores 2110 may be inserted through the exterior region 2120 circumscribed by the tube enclosure 1850. The cylindrical cores 2110 are generally parallel to the axis of symmetry of the tube enclosure 1850. FIG. 22 illustrates a modification of the case of FIG. 21 in which the cores 2110 extend completely through the exterior region 2120 surrounded by the tube enclosure 1850 are replaced by pairs of shortened cores 2210, 2220 in respective halves of the exterior region 2120. The side coils 165, 185 are replaced by a pair of coil windings 2230, 2240 surrounding the respective core pairs 2210, 2220. In this case, the displacement D between the core pairs 2210, 2220 may be changed to adjust the ion density near the wafer center relative to the ion density at the wafer circumference. A wider displacement D reduces the inductive coupling near the wafer center and therefore reduces the plasma ion density at the wafer center. Thus, an additional control element is provided for precisely adjusting ion density spatial distribution across the wafer surface. FIG. 23 illustrates a variation of the case of FIG. 22 in which the separate windings 2230, 2240 are replaced by a single center winding 2310 centered with respect to the core pairs 2210, 2220.

FIGS. 24 and 25 illustrate a case providing even greater uniformity of plasma ion density distribution across the wafer surface. In the case of FIGS. 24 and 25, two torroidal plasma current paths are established that are transverse to one another and are mutually orthogonal. This is accomplished by providing a second wide rectangular hollow enclosure 2420 extending transversely and



orthogonally relative to the first tube enclosure 1850. The second tube enclosure 2420 communicates with the chamber interior through a pair of openings 2430, 2440 through the ceiling 110 and includes an insulating gap 2452. A pair of  
5 side coil windings 2450, 2460 along the sides of the second tube enclosure 2420 maintain a plasma therein and are driven by a second RF power supply 2470 through an impedance match circuit 2480. As indicated in FIG. 24, the two orthogonal  
10 plasma currents coincide over the wafer surface and provide more uniform coverage of plasma over the wafer surface. This case is expected to find particularly advantageous use for processing large wafers of diameters of 10 inches and greater.

15 As in the case of FIG. 17, the case of FIG. 24 creates two mutually orthogonal torroidal plasma current paths over the wafer 120 for enhanced uniformity. The two orthogonal torroidal or closed paths are separate and independently powered as illustrated, but intersect in the process region  
20 overlying the wafer, and otherwise do not interact or otherwise divert or diffuse one another. In order to assure separate control of the plasma source power applied to each one of the orthogonal paths, the frequency of the respective RF generators 180, 2470 of FIG. 24 are different, so that  
25 the operation of the impedance match circuits 175, 2480 is decoupled. For example, the RF generator 180 may produce an RF signal at 11 MHz while the RF generator 2470 may produce an RF signal at 12 MHz. Alternatively, independent operation may be achieved by offsetting the phases of the  
30 two RF generators 180, 2470.

FIG. 26 illustrates a variation of the case of FIG. 18 in which a modified rectangular enclosure 2650 that includes an insulating gap 2658 communicates with the chamber  
35 interior through the chamber side wall 105 rather than through the ceiling 110. For this purpose, the rectangular

enclosure 2650 has a horizontal top section 2652, a pair of downwardly extending legs 2654 at respective ends of the top section 2652 and a pair of horizontal inwardly extending legs 2656 each extending from the bottom end of a respective  
5 one of the downwardly extending legs 2654 to a respective opening 2670, 2680 in the side wall 105.

FIG. 27 illustrates how a second rectangular tube enclosure 2710 including an insulating gap 2752 may be added  
10 to the case of FIG. 26, the second tube enclosure 2710 being identical to the rectangular tube enclosure 2650 of FIG. 26 except that the rectangular tube enclosures 2650, 2710 are mutually orthogonal (or at least transverse to one another). The second rectangular tube enclosure communicates with the  
15 chamber interior through respective openings through the side wall 105, including the opening 2720. Like the case of FIG. 25, the tube enclosures 2650 and 2710 produce mutually orthogonal torroidal plasma currents that coincide over the wafer surface to provide superior uniformity over a broader  
20 wafer diameter. Plasma source power is applied to the interior of the tube enclosures through the respective pairs of side coil windings 165, 185 and 2450, 2460.

FIG. 28A illustrates how the side coils 165, 185, 2450, 2460 may be replaced (or supplemented) by a pair of mutually  
25 orthogonal interior coils 2820, 2840 lying within the external region 2860 surrounded by the two rectangular tube enclosures 2650, 2710. Each one of the coils 2820, 2840 produces the torroidal plasma current in a corresponding one  
30 of the rectangular tube enclosures 2650, 2710. The coils 2820, 2840 may be driven completely independently at different frequencies or at the same frequency with the same or a different phase. Or, they may be driven at the same frequency but with a phase difference (i.e., 90 degrees)  
35 that causes the combined torroidal plasma current to rotate at the source power frequency. In this case the coils 2820,

2840 are driven with the sin and cosine components,  
respectively, of a common signal generator 2880, as  
indicated in FIG. 28A. The advantage is that the plasma  
current path rotates azimuthally across the wafer surface at  
5 a rotational frequency that exceeds the plasma ion frequency  
so that non-uniformities are better suppressed than in prior  
art methods such as MERIE reactors in which the rotation is  
at a much lower frequency.

10 Referring now to FIG. 28B, radial adjustment of plasma  
ion density may be generally provided by provision of a pair  
of magnetic cylindrical cores 2892, 2894 that may be axially  
moved toward or away from one another within the coil 2820  
and a pair of magnetic cylindrical cores 2896, 2898 that may  
15 be axially moved toward or away from one another within the  
coil 2840. As each pair of cores is moved toward one  
another, inductive coupling near the center of each of the  
orthogonal plasma currents is enhanced relative to the edge  
of the current, so that plasma density at the wafer center  
20 is generally enhanced. Thus, the center-to-edge plasma ion  
density may be controlled by moving the cores 2892, 2894,  
2896, 2898.

FIG. 29 illustrates an alternative case of the  
25 invention in which the two tube enclosures 2650, 2710 are  
merged together into a single enclosure 2910 that extends  
360 degrees around the center axis of the reactor that  
constitutes a single plenum. In the case of FIG. 29, the  
plenum 2910 has a half-dome lower wall 2920 and a half-dome  
30 upper wall 2930 generally congruent with the lower wall  
2920. The plenum 2910 is therefore the space between the  
upper and lower half-dome walls 2920, 2930. An insulating  
gap 2921 may extend around the upper dome wall 2920 and/or  
an insulating gap 2931 may extend around the lower dome wall  
35 2930. The plenum 2910 communicates with the chamber  
interior through an annular opening 2925 in the ceiling 110

that extends 360 degrees around the axis of symmetry of the chamber.

5       The plenum 2910 completely encloses a region 2950 above  
the ceiling 110. In the case of FIG. 29, plasma source  
power is coupled into the interior of the plenum 2910 by a  
pair of mutually orthogonal coils 2960, 2965. Access to the  
coils 2960, 2965 is provided through a vertical conduit 2980  
passing through the center of the plenum 2910. Preferably,  
10   the coils 2960, 2965 are driven in quadrature as in the case  
of FIG. 28 to achieve an azimuthally circulating torroidal  
plasma current (i.e., a plasma current circulating within  
the plane of the wafer. The rotation frequency is the  
frequency of the applied RF power. Alternatively, the coils  
15   2960, 2965 may be driven separately at different  
frequencies. FIG. 30 is a top sectional view of the case of  
FIG. 29. FIGS. 31A and 31B are front and side sectional  
views, respectively, corresponding to FIG. 30.

20       The pair of mutually orthogonal coils 2960, 2965 may be  
replaced by any number  $n$  of separately driven coils with  
their winding axes disposed at  $360/n$  degrees apart. For  
example, FIG. 32 illustrates the case where the two coils  
2960, 2965 are replaced by three coils 3210, 3220, 3230 with  
25   winding axes placed at 120 degree intervals and driven by  
three respective RF supplies 3240, 3250, 3260 through  
respective impedance match circuits 3241, 3251, 3261. In  
order to produce a rotating torroidal plasma current, the  
three windings 3210, 3220, 3230 are driven 120 degrees out  
30   of phase from a common power source 3310 as illustrated in  
FIG. 33. The cases of FIGS. 32 and 33 are preferred over  
the case of FIG. 29 having only two coils, since it is felt  
much of the mutual coupling between coils would be around  
rather than through the vertical conduit 2980.

35

FIG. 34 illustrates a case in which the three coils are

outside of the enclosed region 2950, while their inductances are coupled into the enclosed region 2950 by respective vertical magnetic cores 3410 extending through the conduit 2980. Each core 3410 has one end extending above the  
5 conduit 2980 around which a respective one of the coils 3210, 3220, 3230 is wound. The bottom of each core 3410 is inside the enclosed region 2950 and has a horizontal leg. The horizontal legs of the three cores 3410 are oriented at 120 degree intervals to provide inductive coupling to the  
10 interior of the plenum 2910 similar to that provided by the three coils inside the enclosed region as in FIG 32.

The advantage of the flattened rectangular tube enclosures of the cases of FIGS. 18-28 is that the broad  
15 width and relatively low height of the tube enclosure forces the torroidal plasma current to be a wide thin belt of plasma that more readily covers the entire surface of a large diameter wafer. The entirety of the tube enclosure need not be of the maximum width. Instead the outer section  
20 of the tube enclosure farthest from the chamber interior may be necked down, as discussed above with reference to the case of FIG. 20. In this case, it is preferable to provide focusing magnets 1870 at the transition corners between the wide portion 1851 and the narrow section 1852 to force the  
25 plasma current exiting the narrow portion 1852 to spread entirely across the entire width of the wide section 1851. If it is desired to maximize plasma ion density at the wafer surface, then it is preferred that the cross-sectional area of the narrow portion 1852 be at least nearly as great as  
30 the cross-sectional area of the wide portion 1851. For example, the narrow portion 1852 may be a passageway whose height and width are about the same while the wide portion 1851 may have a height that is less than its width.

35 The various cases described herein with air-core coils (i.e., coils without a magnetic core) may instead employ

magnetic-cores, which can be the open-magnetic-path type or the closed-magnetic-core type illustrated in the accompanying drawings. Furthermore, the various cases described herein having two or more torroidal paths driven  
5 with different RF frequencies may instead be driven with same frequency, and with the same or different phases.

FIG. 35 is a version of the case of FIG. 17 in which the mutually transverse hollow conduits are narrowed as in  
10 the case of FIG. 20.

FIG. 36 is a version of the case of FIG. 24 but employing a pair of magnetic cores 3610, 3620 with respective windings 3630, 3640 therearound for connection to  
15 respective RF power sources.

FIG. 37 is a case corresponding to that of FIG. 35 but having three instead of two reentrant conduits with a total of six reentrant ports to the chamber. Having a number of  
20 symmetrically disposed conduits and reentrant ports greater than two (as in the case of FIG. 37) is believed to be particularly advantageous for processing wafers of diameter of 300 mm and greater.

FIG. 38 is a case corresponding to that of FIG. 38 but having three instead of two reentrant conduits with a total of six reentrant ports to the chamber.

FIG. 39 is a case corresponding to that of FIG. 35 in which the external conduits join together in a common plenum  
30 3910.

FIG. 40 is a case corresponding to that of FIG. 36 in which the external conduits join together in a common plenum  
35 4010.

FIG. 41 is a case corresponding to that of FIG. 37 in which the external conduits join together in a common plenum 4110.

5        FIG. 42 is a case corresponding to that of FIG. 38 in which the external conduits join together in a common plenum 4210.

10       FIG. 43 is a case corresponding to that of FIG. 17 in which the external conduits join together in a common plenum 4310.

Advantageous Features:

15       Constricting the torroidal plasma current in the vicinity of the wafer not only improves etch selectivity but at the same time increases the etch rate by increasing the plasma ion density. It is believed no prior reactor has increased etch selectivity by the same mechanism that  
20       increases etch rate or plasma ion density over the workpiece.

Improving etch selectivity by constricting the torroidal plasma current in the vicinity of the wafer or  
25       workpiece can be achieved in the invention in any one of several ways. One way is to reduce the pedestal-to-ceiling or wafer-to-ceiling height. Another is to introduce a gas distribution plate or showerhead over the wafer that constricts the path of the torroidal plasma ion current.  
30       Another way is to increase the RF bias power applied to the wafer or workpiece. Any one or any combination of the foregoing ways of improving etch selectivity may be chosen by the skilled worker in carrying out the invention.

35       Etch selectivity may be further improved in the invention by injecting the reactive process gases locally

(i.e., near the wafer or workpiece) while injecting an inert diluent gas (e.g., Argon) remotely (i.e., into the conduit or plenum). This may be accomplished by providing a gas distribution plate or showerhead directly over and facing the workpiece support and introducing the reactive process gas exclusively (or at least predominantly) through the showerhead. Concurrently, the diluent gas is injected into the conduit well away from the process region overlying the wafer or workpiece. The torroidal plasma current thus becomes not only a source of plasma ions for reactive ion etching of materials on the wafer but, in addition, becomes an agent for sweeping away the reactive process gas species and their plasma-dissociated progeny before the plasma-induced dissociation process is carried out to the point of creating an undesirable amount of free fluorine. This reduction in the residence time of the reactive process gas species enhances the etch selectivity relative to photoresist and other materials, a significant advantage.

Great flexibility is provided in the application of RF plasma source power to the torroidal plasma current. As discussed above, power is typically inductively coupled to the torroidal plasma current by an antenna. In many cases, the antenna predominantly is coupled to the external conduit or plenum by being close or next to it. For example, a coil antenna may extend alongside the conduit or plenum. However, in other cases the antenna is confined to the region enclosed between the conduit or plenum and the main reactor enclosure (e.g., the ceiling). In the latter case, the antenna may be considered to be "under" the conduit rather than alongside of it. Even greater flexibility is afforded by cases having a magnetic core (or cores) extending through the enclosed region (between the conduit and the main chamber enclosure) and having an extension beyond the enclosed region, the antenna being wound around the core's extension. In this case the antenna is inductively coupled



via the magnetic core and therefore need not be adjacent the torroidal plasma current in the conduit. In one such case, a closed magnetic core is employed and the antenna is wrapped around the section of the core that is furthest away  
5 from the torroidal plasma current or the conduit. Therefore, in effect, the antenna may be located almost anywhere, such as a location entirely remote from the plasma chamber, by remotely coupling it to the torroidal plasma current via a magnetic core.

10

Finally, plasma distribution over the surface of a very large diameter wafer or workpiece is uniform. This is accomplished in one case by shaping the torroidal plasma current as a broad plasma belt having a width preferably  
15 exceeding that of the wafer. In another case, uniformity of plasma ion density across the wafer surface is achieved by providing two or more mutually transverse or orthogonal torroidal plasma currents that intersect in the process region over the wafer. The torroidal plasma currents flow  
20 in directions mutually offset from one another by  $360/n$ . Each of the torroidal plasma currents may be shaped as a broad belt of plasma to cover a very large diameter wafer. Each one of the torroidal plasma currents may be powered by a separate coil antenna aligned along the direction of the  
25 one torroidal plasma current. In one preferred case, uniformity is enhanced by applying RF signals of different phases to the respective coil antennas so as to achieve a rotating torroidal plasma current in the process region overlying the wafer. In this preferred case, the optimum  
30 structure is one in which the torroidal plasma current flows in a circularly continuous plenum communicating with the main chamber portion through a circularly continuous annular opening in the ceiling or side wall. This latter feature allows the entire torroidal plasma current to rotate  
35 azimuthally in a continuous manner.

### Controlling Radial Distribution of Plasma Ion Density:

FIG. 44 illustrates a plasma reactor similar to that illustrated in FIG. 17A having a pair of orthogonal external reentrant tubes 150-1, 150B2. RF power is coupled into the tubes by respective annular magnetic cores 1015-1, 1015-2 excited by respective RF-driven coils 170-1, 170-2, as described above with reference to FIG. 17A. However, in FIG. 44 the external tubes 150-1, 150-2 are rectangular as in FIG. 24 rather than being round in cross-sectional shape. Moreover, the horizontal section of the lower tube 150-1 is not flat but rather has a dip 4410 at its middle. The dip 4410 permits the upper external tube 150-2 to nest closer to the reactor ceiling 110. This feature shortens the path length in the upper tube 150-2, thereby reducing plasma losses in the upper tube 150-2. In fact, the shape of the dip 4410 may be selected to at least nearly equalize the path length through the upper and lower external tubes 150-1, 150-2. The reactor of FIG. 44, like the reactors of FIGS. 2 and 26, has a gas distribution plate 210 on the ceiling 110 (or forming the ceiling 110 itself) and overlying the wafer 120.

The dip 4410 is limited in that a vertical space remains between the top surface of the ceiling 110 and a bottom corner 4422 formed on the lower tube 150-1 at the apex of the dip 4410. The vertical space accommodates an electromagnet assembly 4430 that enhances plasma ion density over the center of the wafer 120. The electromagnet assembly 4430 includes a narrow elongate cylindrical pole piece 4440 formed of a magnetizable metal such as iron or steel (for example) and a coil 4450 of insulated conductive wire (e.g., copper wire) wrapped around the pole piece 4440. The cylindrical axis of the pole piece 4440 coincides with the axis of symmetry of the cylindrical chamber 100, so that the axis of the pole piece 4440 intersects the center of the

wafer 120. The coil 4450 may be wrapped directly on the pole piece 4440 or, as illustrated in FIG. 45, may be wrapped around a mandril 4460 encircling the pole piece 4440. FIG. 45 shows that the coil 4450 may be wrapped  
5 around a section 4440-1 of the pole piece 4440 that extends above the ceiling 110. The lower section 4440-2 of the pole piece 4440 that is inside the ceiling 110 terminates within the gas manifold 220 of the gas distribution plate 210.

10 For efficiency, it is desirable to place the source of the plasma-confining magnetic field as close to the plasma as practical without disturbing gas flow within the gas distribution plate 210. For this purpose, the portion of the lower pole piece section 4440-2 that is inside the gas  
15 manifold 220 is a very narrow cylindrical end piece 4470 that terminates the pole piece 4440. The end piece 4470 extends the magnetic field lines of the pole piece 4440 near the bottom of the gas distribution plate to enhance the effect of the magnetic field on the plasma. The diameter of  
20 the end piece 4470 is sufficiently reduced so that it does not appreciably interfere with gas flow within the gas manifold 210. Moreover, such a reduced diameter brings the peak of the radial component of the magnetic field nearer the center axis.

25 FIG. 46 illustrates one case of the end piece 4470 having a tapered bottom 4475 terminated in a nipple 4477. FIG. 47 illustrates a case of the end piece 4470 in which the bottom 4476 is flat. FIG. 48 illustrates a case of the  
30 end piece 4470 in which the bottom 4478 is round.

In one implementation, pole piece 4440 has a diameter of about 3.5 cm (such that the diameter of the approximately 60 turn coil 4450 is about 6 cm) and is about 12 cm long.  
35 The pole piece 4440 is extended about 2 cm (to a total of about 14 cm) with a smaller diameter extension of about 1 cm

diameter. The bottom of the extension region of the pole piece 4440 is about 1.5 cm from the top of the plasma region. The material composition of pole piece 4440 is selected to have sufficiently high permeability (e.g.,  $\mu_r >$  or = 100) and high saturation flux density (e.g.  $B_{sat} > 1000$  gauss) to maximize the magnetic flux density in the region below the pole piece 4440 with minimum magnetizing force and current. Note that because the magnetic path is "open" with pole piece 4440 (not closed within the pole piece), the effective permeability is reduced relative to the material permeability. Depending on the length/diameter ratio of the pole piece 4440, the  $\mu_r$  "effective" is typically reduced to on the order of 10.

An optional shield 4479 of magnetic material such as iron shields plasma in the pair of tubes 150-1, 150-2 from the D.C. magnetic field of the electromagnet assembly 4430. The shield 4479 includes an overhead plate 4479a and a cylindrical skirt 4479b.

In the case of the gas distribution plate 210 illustrated in FIG. 45, a top plate 4480 is divided into radially inner and outer sections 4480a, 4480b, each having many small gas flow holes 4481 extending through it, the inner and outer sections having annular flanges 4482-1, 4482-2, 4482-3, 4482-4, forming vertical walls supporting the bottom surface of the ceiling 210 and forming therewith inner and outer gas manifolds 4483a, 4483b separated by a wall formed by the annular flanges 4482-2, 4482-3. In one case, there is no wall between the inner and outer gas manifolds, so as to avoid any discontinuity in gas distribution within the chamber that such a wall may cause. A gas mixing layer 4484 below the top plate 4480 diverts gas flow from a purely vertical flow direction and thereby induces multi-directional (or turbulent) gas flow that

improves uniform mixing of gases of different molecular weights. Such diverting of the gas flow from a purely downward flow direction has the added benefit of suppressing high velocity gas flow effects, in which high velocity gas flow through gas distribution plate orifices directly over the wafer would form localized concentrations of process gas on the wafer surface that disrupt process uniformity. Suppression of high velocity gas flow effects enhances uniformity.

10

The gas mixing layer 4484 may consist of metal or ceramic foam of the type well-known in the art. Or, as shown in FIG. 49, the gas mixture layer 4484 may consist of plural perforation plates 4484-1, 4484-2 each having many small gas orifices drilled through it, the holes in one perforation plate being offset from the holes in the other perforation plate. A bottom plate 4485 of the gas distribution plate 210 has many sub-millimeter gas injection holes 4486 drilled through it with large counterbored holes 4487 at the top of the bottom plate 4485. In one example, the sub-millimeter holes were between 10 and 30 mils in diameter, the counterbored holes were about 0.06 inch in diameter and the bottom plate 4485 had a thickness of about 0.4 inch. Inner and outer gas feed lines 4490, 4492 through the ceiling 110 furnish gas to the inner and outer top plates 4480a, 4480b, so that gas flow in radially inner and outer zones of the chamber may be controlled independently as a way of adjusting process uniformity.

30 It is believed that the radial component of the D.C. magnetic field produced by the electromagnet assembly 4430 affects the radial distribution of plasma ion density, and that it is this radial component of the magnetic field that can be exploited to enhance plasma ion density near the center of the chamber. It is believed that such enhancement of plasma ion density over the wafer center arises from the

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interaction of the D.C. magnetic field radial component with the plasma sheath electric field at the wafer surface producing azimuthal plasma currents tending to confine plasma near the wafer center. In absence of the D.C. magnetic field, the phenomenon of a reduced plasma ion density at the center of the chamber extends over a very small circular zone confined closely to the center of the wafer 120, because in general the reactor of FIG. 44 tends to have an exceptionally uniform plasma ion density even in absence of a correcting magnetic field. Therefore, correction of the center-low plasma ion density distribution requires a D.C. magnetic field having a relatively large radial component very near the center of the chamber or wafer 120. The small diameter of the magnetic pole piece 4440 produces a magnetic field having a large radial component very close to the center of the wafer 120 (or center of the chamber). In accordance with conventional practice, the center is the axis of symmetry of the cylindrical chamber at which the radius is zero. FIG. 51 illustrates the distribution of the magnetic field in an elevational view of the processing region over the wafer 120 between the wafer 120 and the gas distribution plate 210. The vectors in FIG. 51 are normalized vectors representing the direction of the magnetic field at various locations. FIG. 52 illustrates the magnetic flux density of the radial component of the magnetic field as a function of radial location, one curve representing the radial field flux density near the bottom surface of the gas distribution plate 210 and the other curve representing the radial field flux density near the surface of the wafer 120. The peak of the flux density of the radial magnetic field component is very close to the center, namely at about a radius of only one inch both at the ceiling and at the wafer. Thus, the radial component of the magnetic field is tightly concentrated near the very small diameter region within which the plasma ion density tends to be lowest. Thus, the

distribution of the radial component of the D.C. magnetic field produced by the electromagnet assembly 4430 generally coincides with the region of low plasma ion density near the center of the chamber.

5

As mentioned above, it is felt that the radial component of the D.C. magnetic field interacts with the vertically oriented electric field of the plasma sheath near the wafer center to produce an azimuthally directed force that generally opposes radial travel of plasma. As a result, plasma near the center of the wafer is confined to enhance processing within that region.

A basic approach of using the electromagnet assembly 4430 in an etch reactor is to find a D.C. current flow in the coil that produces the most uniform etch rate radial distribution across the wafer surface, typically by enhancing plasma ion density at the center. This is the likeliest approach in cases in which the wafer-to-ceiling gap is relatively small (e.g., one inch), since such a small gap typically results in a center-low etch rate distribution on the wafer. For reactors having a larger gap (e.g., two inches or more), the etch rate distribution may not be center low, so that a different D.C. current may be needed. Of course, the electromagnet assembly 4430 is not confined to applications requiring improved uniformity of plasma ion density across the wafer surface. Some applications of the electromagnet assembly may require an electromagnet coil current that renders the plasma ion density less uniform. Such applications may involve, for example, cases in which a field oxide thin film layer to be etched has a non-uniform thickness distribution, so that uniform results can be obtained only by providing nonuniform plasma ion density distribution that compensates for the nonuniform field oxide thickness distribution. In such a case, the D.C. current in the electromagnet assembly can be selected to provide the

requisite nonuniform plasma ion distribution.

As shown in FIG. 45, the plasma reactor may include a set of integrated rate monitors 4111 that can observe the etch rate distribution across the wafer 120 during the etch process. Each monitor 4111 observes the interference fringes in light reflected from the bottom of contact holes while the holes are being etched. The light can be from a laser or may be the luminescence of the plasma. Such real time observation can make it possible to determine changes in etch rate distribution across the wafer that can be instantly compensated by changing the D.C. current applied to the electromagnet assembly 4430.

FIG. 53 shows one way of independently controlling process gas flow to the inner and outer gas feed lines 4490, 4492. In FIG. 53, one set of gas flow controllers 5310, 5320, 5330 connected to the inner gas feed line 4490 furnish, respectively, argon, oxygen and a fluoro-carbon gas, such as  $C_4F_6$ , to the inner gas feed line 4490. Another set of gas flow controllers 5340, 5350, 5360 furnish, respectively, argon, oxygen and a fluoro-carbon gas, such as  $C_4F_6$ , to the outer gas feed line 4492. FIG. 54 shows another way of independently controlling process gas flow to the inner and outer gas feed lines 4490, 4492. In FIG. 54, a single set of gas flow controllers 5410, 5420, 5430 furnishes process gases (e.g., argon, oxygen and a fluoro-carbon gas) to a gas splitter 5440. The gas splitter 5440 has a pair of gas or mass flow controllers (MFC's) 5442, 5444 connected, respectively, to the inner and outer gas feed lines 4490, 4492. In addition, optionally another gas flow controller 5446 supplies purge gas such as Argon or Neon to the outer gas feed line 4492.

One problem in processing a large diameter wafer is that the torroidal or reentrant plasma current must spread



out evenly over the wide surface of the wafer. The tubes 150 typically are less wide than the process area. The need then is to broaden the plasma current to better cover a wide process area as it exits a port 155 or 160. As related  
5 problem is that the reactor of FIG. 44 (or any of the reactors of FIGS. 1-43) can experience a problem of non-uniform plasma ion density and consequent "hot spot" or small region 5505 of very high plasma ion density near a port 155 or 160 of the reentrant tube 150, as shown in FIG.  
10 55A. Referring to FIGS. 55A-56B, these problems are addressed by the introduction of a plasma current flow splitter 5510 at the mouth of each port (e.g., the port 155 as shown in FIG. 55A). The splitter 5510 tends to force the plasma current to widen while at the same time reducing  
15 plasma ion density in the vicinity of the region 5505 where a hot spot might otherwise form. The tube 150 can have a widened termination section 5520 at the port 155, the termination section 5520 having a diameter nearly twice as great as that of the remaining portion of the tube 150. The  
20 plasma current flow splitter 5510 of FIG. 55A is triangular in shape, with one apex facing the interior of the tube 150 so as to force the plasma current flowing into the chamber 100 from the tube 150 to spread out so as to better fill the larger diameter of the termination section 5520. This  
25 current-spreading result produced by the triangular splitter 5510 tends to widen the plasma current and reduces or eliminates the "hot spot" in the region 5505.

The optimum shape of the splitter 5510 depends at least  
30 in part upon the separation distance  $S$  between the centers of opposing ports 155, 160. If the splitter is too long in the direction of plasma flow (i.e., the vertical direction in FIG. 55A), then current flow along the divided path tends to be unbalanced, with all current flowing along one side of  
35 the splitter 5510. On the other hand, if the splitter 5510 is too short, the two paths recombine before the plasma

current appreciably widens.

For example, in a chamber for processing a 12-inch diameter wafer, the separation distance  $S$  can be about 20.5 inches, with a tube width  $w$  of 5 inches, a tube draft  $d$  of 1.75 inches and an expanded termination section width  $W$  of 8 inches. In this case, the juxtaposition of the port 155 relative to the 12 inch wafer would be as shown in the plan view of FIG. 56C. In this particular example, the height  $h$  of the splitter 5510 should be about 2.5 inches, with the angle of the splitter's apex 5510a being about 75 degrees, as shown in FIG. 57. In addition, the length  $L$  of the termination section 5520 should equal the height  $h$  of the splitter 5510.

On the other hand, for a separation distance  $S$  of 16.5 inches, an optimum splitter 5510' is illustrated in FIG. 58. The angle of the splitter apex in this case is preferably about 45 degrees, the triangular portion being terminated in a rectangular portion having a width of 1.2 inches and a length such that the splitter 5510' has a height  $h$  of 2.5 inches. The height and apex angle of the splitter 5510 or 5510' must be sufficient to reduce plasma density in the region 5505 to prevent formation of a hot spot there. However, the height  $h$  must be limited in order to avoid depleting plasma ion density at the wafer center.

FIGS. 59A and 59B illustrate splitters for solving the problem of plasma ion density non-uniformity near the entrance ports of a reentrant tube 2654 in which plasma current flow through each port is in a horizontal direction through the chamber side wall 105, as in the reactor of FIG. 26. Each splitter 5910 has its apex 5910a facing the port 2680.

FIGS. 60, 61 and 62 illustrate an implementation like

that of FIG. 17A, except that the chamber side wall 105 is rectangular or square and the vertically facing ports 140-1, 140-2, 140-3 and 140-4 through the ceiling 110 are located over respective corners 105a, 105b, etc. of the rectangular or square side wall 105. A floor 6020 in the plane of the wafer 120 faces each port and, together with the corner-forming sections of the rectangular side wall 105, forces incoming plasma current to turn toward the processing region overlying the wafer 120. In order to reduce or eliminate a hot spot in plasma ion density in the region 6030, a triangular plasma current flow splitter 6010 is placed near each respective corner 105a, 105b, etc., with its apex 6010a facing that corner. In the implementation of FIG. 61, the splitter apex 6010a is rounded, but in other implementations it may be less rounded or actually may be a sharp edge. FIG. 63 illustrates a portion of the same arrangement but in which the edge 6010b of the splitter 6010 facing the wafer 120 is located very close to the wafer 120 and is arcuately shaped to be congruent with the circular edge of the wafer 120. While the splitter 6010 of FIG. 60 extends from the floor 6020 to the ceiling 110, FIG. 64 illustrates that the height of the splitter 6010 may be less, so as to allow some plasma current to pass over the splitter 6010.

As will be discussed in greater detail below with respect to certain working examples, the total path length traversed by the reentrant plasma current affects plasma ion density at the wafer surface. This is because shorter path length places a higher proportion of the plasma within the processing region overlying the wafer, reduces path length-dependent losses of plasma ions and reduces surface area losses due to plasma interaction with the reentrant tube surface. Therefore, the shorter length tubes (corresponding to a shorter port separation distance  $S$ ) are more efficient. On the other hand, a shorter separation distance  $S$  affords less opportunity for plasma current flow separated at its

center by the triangular splitter 5510 to reenter the center region after passing the splitter 5510 and avoid a low plasma ion density at the wafer center. Thus, there would appear to be a tradeoff between the higher efficiency of a smaller port separation distance S and the risk of depressing plasma ion density at the wafer center in the effort to avoid a plasma hot spot near each reentrant tube port.

This tradeoff is ameliorated or eliminated in the case of FIGS. 65A, 65B and 66, by using a triangular splitter 6510 that extends at least nearly across the entire width W of the termination section 5520 of the port and is shaped to force plasma current flow away from the inner edge 6610 of the port and toward the outer edge 6620 of the port. This feature leaves the port separation distance S unchanged (so that it may be as short as desired), but in effect lengthens the plasma current path from the apex 6510a of the splitter to the center of the wafer 120. This affords a greater opportunity for the plasma current flow split by the splitter 6510 to rejoin at its center before reaching the wafer or center of the wafer. This feature better avoids depressing plasma ion density at the wafer center while suppressing formation of plasma hot spots at the reentrant tube ports.

As illustrated in FIGS. 65A, 65B and 66, each splitter 6510 presents an isocetes triangular shape in elevation (FIG. 65B) and a rectangular shape from the top (FIG. 65A). The side view of FIG. 66 reveals the sloping back surface 6610c that extends downwardly toward the outer edge 6620 of the port. It is the sloping back surface 6610c that forces the plasma current toward the back edge 6620 thereby effectively lengthening the path from the top of the apex 6510a to the wafer center, which is the desired feature as set forth above. The rectangular opening of the port 150 is

narrowed in the radial direction (the short dimension) by the sloped wall or sloping back surface 6610b from about 2" at top to about 3/4" at the bottom. This pushes the inner port edge about 1-1/4" radially farther from the wafer (thus achieving the desired increase in effective port separation distance). In addition, the port 150 has the full triangular splitter 6510 in the azimuthal direction (the long or 8" wide dimension of the opening 150).

The plasma current splitter 5510 or 6510 may have coolant passages extending within it with coolant ports coupled to similar ports in the reactor body to regulate the temperature of the splitter. For this purpose, the plasma current splitter 5510 or 6510 is formed of metal, since it easily cooled and is readily machined to form internal coolant passages. However, the splitter 5510 or 6510 may instead be formed of another material such as quartz, for example.

FIG. 67 illustrates another way of improving plasma uniformity in the torroidal source reactor of FIG. 24 by introducing a set of four annular electromagnets 6710, 6720, 6730, 6740 along the periphery of the reactor, the windings of each electromagnet being controlled by a magnet current controller 6750. The electric currents in the four electromagnets may be driven in any one of three modes: (1) in a first mode, a sinusoidal mode, the coils are driven at the same low frequency current in phase quadrature to produce a magnetic field that rotates about the axis of symmetry of the reactor at the low frequency of the source; (2) in a second mode, a configurable magnetic field mode, the four electromagnets 6710, 6720, 6730, 6740 are grouped into opposing pairs of adjacent electromagnets, and each pair is driven with a different D.C. current to produce a magnetic field gradient extending diagonally between the opposing pairs of adjacent electromagnets, and this grouping

is rotated so that the magnetic field gradient is rotated to isotropically distribute its effects over the wafer;

(3) in a third mode, the four electromagnets are all driven with the same D.C. current to produce a cusp-shaped magnetic field having an axis of symmetry coinciding generally with the axis of symmetry of the reactor chamber.

As shown in FIG. 1, a pumping annulus is formed between the cylindrical wafer support pedestal 115 and the cylindrical side wall 105, gases being evacuated via the pumping annulus by the vacuum pump 135. Plasma current flow between the opposing ports of each reentrant tube 150 can flow through this pumping annulus and thereby avoid flowing through the processing region between the wafer 120 and the gas distribution plate 210. Such diversion of plasma current flow around the process region can occur if the chamber pressure is relatively high and the wafer-to-ceiling gap is relatively small and/or the conductivity of the plasma is relatively low. To the extent this occurs, plasma ion density in the process region is reduced. This problem is solved as shown in FIGS. 68 and 69 by the introduction of radial vanes 6910, 6920, 6930, 6940 blocking azimuthal plasma current flow through the pumping annulus. In one implementation, the vanes 6910, 6920, 6930, 6940 extend up to but not above the plane of the wafer 120, to allow insertion and removal of the wafer 120. However, in another implementation the vanes may retractably extend above the plane of the wafer to better confine the plasma current flow within the processing region overlying the wafer 120. This may be accomplished by enabling the wafer support pedestal 115 to move up and down relative to the vanes, for example. In either case, the vanes 6910, 6920, 6930, 6940 prevent plasma current flow through the pumping annulus, and, if the vanes can be moved above the plane of the wafer 120, they also reduce plasma current flow through the upper region overlying the pumping annulus. By thus preventing diversion

of plasma current flow away from the processing region overlying the wafer, not only is plasma ion density improved in that region but process stability is also improved.

5       As mentioned previously herein, the magnetic core used to couple RF power to each reentrant tube 150 tends to crack or shatter at high RF power levels. It is believed this problem arises because magnetic flux is not distributed uniformly around the core. Generally, one winding around  
10 the core has a high current at high RF power levels. This winding can be, for example, a secondary winding that resonates the primary winding connected to the RF generator. The secondary winding is generally confined to a narrow band around the core, magnetic flux and heating being very  
15 high within this band **and** much lower elsewhere in the core. The magnetic core must have a suitable permeability (e.g., a permeability between about 10 and 200) to avoid self-resonance at high frequencies. A good magnetic core tends to be a poor heat conductor (low thermal conductivity) and  
20 be readily heated (high specific heat), and is therefore susceptible to localized heating. Since the heating is localized near the high current secondary winding and since the core tends to be brittle, it cracks or shatters at high RF power levels (e.g., 5 kiloWatts of continuous power).

25       This problem is solved in the manner illustrated in FIGS. 70 through 74 by more uniformly distributing RF magnetic flux density around the annular core. FIG. 70 illustrates a typical one of the magnetic cores 1015 of FIG.  
30 17A. The core 1015 is formed of a high magnetic permeability material such as ferrite. The primary winding 170 consists of about two turns of a thin copper band optionally connected through an impedance match device 175 to the RF generator 180. High current flow required for  
35 high magnetic flux in the core 1015 occurs in a resonant

secondary winding 7010 around the core 1015. Current flow in the secondary winding 7010 is about an order of magnitude greater than current flow in the primary winding. In order to uniformly distribute magnetic flux around the core 1015, the secondary winding 7010 is divided into plural sections 7010a, 7010b, 7010c, etc., that are evenly distributed around the annular core 1015. The secondary winding sections 7010a, etc., are connected in parallel. Such parallel connection is facilitated as illustrated in FIGS. 71A and 71B by a pair of circular copper buses 7110, 7120 extending around opposite sides of the magnetic core 1015. Opposing ends of each of the secondary windings 7010a, 7010b, etc., are connected to opposite ones of the two copper buses 7110, 7120. The copper buses 7110, 7120 are sufficiently thick to provide an extremely high conductance and low inductance, so that the azimuthal location of any particular one of the secondary winding sections 7010a, 7010b, etc. makes little or no difference, so that all secondary winding sections function as if they were equidistant from the primary winding. In this way, magnetic coupling is uniformly distributed around the entire core 1015.

Because of the uniform distribution of magnetic flux achieved by the foregoing features, the primary winding may be placed at any suitable location, typically near a selected one of the plural distributed secondary winding sections 7110a, 7110b, 7110c, etc. However, in one implementation, the primary winding is wrapped around or on a selected one of the plural distributed secondary winding sections 7110a, 7110b, 7110c, etc.

FIG. 72 is a representation of the distributed parallel inductances formed by the parallel secondary winding sections 7010a, 7010b, etc., and FIG. 73 shows the circular topology of these distributed inductances. In order to



provide resonance at the frequency of the RF generator 180, plural distributed capacitors 7130 are connected in parallel across the two copper buses 7110, 7120. The plural capacitors 7030 are distributed azimuthally around the magnetic core 1015. Each capacitor 7030 in one implementation was about 100 picoFarads. The equivalent circuit of the distributed inductances and capacitances associated with the secondary winding 7010 is illustrated in FIG. 24.

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Referring to FIG. 71B, the secondary winding sections 7010a, 7010b, etc., can have the same number of turns. In the case of FIG. 71B, there are six secondary winding sections 7010a-7010f, each section having three windings. The skilled worker can readily select the number of secondary winding sections, the number of windings in each section and the capacitance of the distributed capacitors 7030 to achieve resonance at the frequency of the RF generator 180. The copper band stock used to form the primary and secondary windings around the core 1015 can be, for example, 0.5 inch wide and 0.020 inch thick copper stripping. The two copper buses 7110, 7120 are very thick (e.g., from 0.125 inch to 0.25 inch thick) and wide (e.g., 0.5 inch wide) so that they form extremely low resistance, low inductance current paths. The core 1015 may consist of a pair of stacked 1 inch thick ferrite cores with a 10 inch outer diameter and an 8 inch inner diameter. Preferably, the ferrite core 1015 has a magnetic permeability  $\mu=40$ . The foregoing details are provided by way of example only, and any or all of the foregoing values may require modification for different applications (e.g., where, for example, the frequency of the RF generator is modified).

We have found that the feature of distributed inductances illustrated in FIGS. 71A and 71B solves the

problem of breakage of the magnetic core experienced at sustained high RF power levels (e.g., 5 kiloWatts).

FIG. 75 illustrates the equivalent circuit formed by the core and windings of FIGS. 71A and 71B. In addition to the primary and secondary windings 170 and 7010 around the core 1015, FIG. 75 illustrates the equivalent inductive and capacitive load presented by the plasma inductively coupled to the core 1015. The case of FIGS. 70-75 is a transformer coupled circuit. The purpose of the secondary winding 7010 is to provide high electric current flow around the magnetic core 1015 for enhanced power coupling via the core. The secondary winding 7010 achieves this by resonating at the frequency of the RF generator. Thus, the high current flow and power coupling via the magnetic core 1015 occurs in the secondary winding 7010, so that virtually all the heating of the core 1015 occurs at the secondary winding 7010. By thus distributing the secondary winding 7010 around the entire circumference of the core 1015, this heating is similarly distributed around the core to avoid localized heating and thereby prevent shattering the core at high RF power levels.

The distributed winding feature of FIGS. 71A and 71B can be used to implement other circuit topologies, such as the auto transformer circuit of FIG. 76. In the auto transformer circuit of FIG. 76, the winding 7010 around the core 1015 is distributed (in the manner discussed above with reference to FIGS. 70-74) and has a tap 7610 connected through the impedance match circuit 175 to the RF generator 180. The distributed capacitors 7030 provide resonance (in the manner discussed above). As in FIG. 70, the core 7010 is wrapped around the reentrant tube 150 so that power is inductively coupled into the interior of the tube 150. The circuit topologies of FIGS. 75 and 76 are only two examples of the various topologies that can employ distributed windings around the magnetic core 1015.

In one implementation, the impedance match circuits 175a, 175b employed frequency tuning in which the frequency of each RF generator 180a, 180b is controlled in a feedback circuit in such a way as to minimize reflected power and maximize forward or delivered power. In such an implementation, the frequency tuning ranges of each of the generators 180a, 180b are exclusive, so that their frequencies always differ, typically on the order of a 0.2 to 2 MHz difference. Moreover, their phase relationship is random. This frequency difference can improve stability. For example, instabilities can arise if the same frequency is used to excite plasma in both of the orthogonal tubes 150-1, 150-2. Such instabilities can cause the plasma current to flow through only three of the four ports 155, 160, for example. This instability may be related to the phase difference between the torroidal plasma currents in the tubes. One factor facilitating plasma stability is isolation between the two plasma currents of the pair of orthogonal tubes 150-1, 150-2. This isolation is provided mainly by the plasma sheaths of the two plasma currents. The D.C. break or gap 152 of each of the reentrant tubes 150-1, 150-2 also enhances plasma stability.

While the D.C. break or gap 152 in each of the orthogonal tubes is illustrated in FIG. 44 as being well-above the chamber ceiling 110, it may in fact be very close to or adjacent the ceiling. Such an arrangement is employed in the implementation of FIG. 77, in which the case of FIG. 55A is modified so that the termination section 5520 electrically floats so that its potential follows oscillations of the plasma potential. This solves a problem that can be referred to as a "hollow cathode" effect near each of the ports 155, 160 that creates non-uniform plasma distribution. This effect may be referred to as an electron multiplication cavity effect. By permitting all of the

conductive material near a port to follow the plasma potential oscillations, the hollow cathode effects are reduced or substantially eliminated. This is achieved by electrically isolating the termination section 5520 from the grounded chamber body by locating a D.C. break or gap 152' at the juncture between the reentrant tube termination section 5520 and the top or external surface of the ceiling 110. (The gap 152' may be in addition to or in lieu of the gap 152 of FIG. 44.) The gap 152' is filled with an insulative annular ring 7710, and the termination section 5520 of FIG. 77 has a shoulder 7720 resting on the top of the insulative ring 7710. Moreover, there is an annular vacuum gap 7730 of about 0.3 to 3 mm width between the ceiling 110 and the termination section 5520. In one implementation, the tube 150 and the termination section 5520 are integrally formed together as a single piece. The termination section 5520 is preferably formed of metal so that internal coolant passages may be formed therein.

FIGS. 44-77 illustrate cases in which the uniformity control magnet is above the processing region. FIG. 78 illustrates that the magnet pole 4440 may be placed below the processing region, or under the wafer support pedestal 115.

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#### Working Examples:

An etch process was conducted on blanket oxide wafers at a chamber pressure of 40 mT, 4800 watts of 13.56 MHz RF bias power on the wafer pedestal and 1800 Watts of RF source power applied to each reentrant tube 150 at 11.5 MHz and 12.5 MHz, respectively. The magnetic field produced by the electromagnet assembly 4430 was set at the following levels in successive steps: (a) zero, (b) 6 Gauss and (c) 18 Gauss (where the more easily measured axial magnetic field component at the wafer center was observed rather than the

power applied to each reentrant tube 150 at 11.5 MHz and 12.5 MHz, respectively. The magnetic field produced by the electromagnet assembly 4430 was set at the following levels in successive steps: (a) zero, (b) 6 Gauss and (c) 18 Gauss  
5 (where the more easily measured axial magnetic field component at the wafer center was observed rather than the more relevant radial component). The observed etch rate distribution on the wafer surface was measured, respectively, as (a) center low with a standard deviation of  
10 about 2% at zero Gauss, (b) slightly center fast with a standard deviation of about 1.2 % at 6 Gauss, and (c) center fast with a standard deviation of 1.4%. These examples demonstrate the ability to provide nearly ideal compensation (step b) and the power to overcompensate (step c).

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To test the effective pressure range, the chamber pressure was increased to 160 mT and the electromagnet's field was increased in three steps from (a) zero Gauss, to (b) 28 Gauss and finally to (c) 35 Gauss (where the more  
20 easily measured axial magnetic field component at the wafer center was observed rather than the more relevant radial component). The observed etch rate was, respectively, (a) center slow with a standard deviation of about 2.4%, center fast with a standard deviation of about 2.9% and center fast  
25 with a standard deviation of about 3.3%. Obviously, the step from zero to 28 Gauss resulted in overcompensation, so that a somewhat smaller magnetic field would have been ideal, while the entire exercise demonstrated the ability of the electromagnet assembly 4430 to easily handle very high  
30 chamber pressure ranges. This test was severe because at higher chamber pressures the etch rate distribution tends to be more severely center low while, at the same time, the decreased collision distance or mean free path length of the higher chamber pressure makes it more difficult for a given  
35 magnetic field to effect plasma electrons or ions. This is because the magnetic field can have no effect at all unless

the corresponding Larmour radius of the plasma electrons or ions (determined by the strength of the magnetic field and the mass of the electron or ion) does not exceed the plasma collision distance. As the collision distance decreases  
5 with increasing pressure, the magnetic field strength must be increased to reduce the Larmour radius proportionately. The foregoing examples demonstrate the power of the electromagnet assembly to generate a sufficiently strong magnetic field to meet the requirement of a small Larmour  
10 radius.

Another set of etch processes were carried out on oxide wafers patterned with photoresist at 35 mT under similar conditions, and the current applied to the electromagnet  
15 assembly 4430 was increased in five steps from (a) 0 amperes, (b) 5 amperes, (c) 6 amperes, (d) 7 amperes and (e) 8 amperes. (In this test, a current of 5 amperes produces about 6 gauss measured axial magnetic field component at the wafer center.) At each step, the etch depths of high aspect  
20 ratio contact openings were measured at both the wafer center and the wafer periphery to test center-to-edge etch rate uniformity control. The measured center-to-edge etch rate differences were, respectively, (a) 13.9% center low, (b) 3.3% center low, (c) 0.3% center low, (d) 2.6% center  
25 high and (e) 16.3% center high. From the foregoing, it is seen that the ideal electromagnet current for best center-to-edge uniformity is readily ascertained and in this case was about 6 amperes.

30 A set of etch processes were carried out on blanket oxide wafers to test the efficacy of the dual zone gas distribution plate 210 of FIG. 44. In a first step, the gas flow rates through the two zones were equal, in a second step the inner zone had a gas flow rate four times that of  
35 the outer zone and in a third step the outer zone had a gas flow rate four times that of the inner zone. In each of

these steps, no current was applied to the electromagnet assembly 4430 so that the measurements taken would reflect only the effect of the dual zone gas distribution plate 210. With gas flow rates of the two zones equal in the first  
5 step, the etch rate distribution was slightly center high with a standard deviation of about 2.3%. With the inner zone gas flow rate at four times that of the outer zone, the etch rate distribution was center fast with a standard deviation of about 4%. With the outer zone gas flow rate at  
10 four times that of the inner zone, the etch rate distribution was center slow with a standard deviation of about 3.4%. This showed that the dual zone differential gas flow rate feature of the gas distribution plate 210 can be used to make some correction to the etch rate distribution.  
15 However, the gas flow rate control directly affects neutral species distribution only, since none of the incoming gas is (or should be) ionized. On the other hand, etch rate is directly affected by plasma ion distribution and is not as strongly affected by neutral distribution, at least not  
20 directly. Therefore, the etch rate distribution control afforded by the dual zone gas distribution plate, while exhibiting some effect, is necessarily less effective than the magnetic confinement of the electromagnet assembly 4430 which directly affects plasma electrons and thus ions.

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The dependency of the electromagnet assembly 4430 upon the reentrant torroidal plasma current was explored. First a series of etch processes was carried out on blanket oxide wafers with no power applied to the torroidal plasma source,  
30 the only power being 3 kiloWatts of RF bias power applied to the wafer pedestal. The electromagnet coil current was increased in four steps of (a) zero amperes, (b) 4 amperes, (c) 6 amperes and (d) 10 amperes. The etch rate distribution was observed in the foregoing steps as (a)  
35 center high with a standard deviation of 2.87%, (b) center high with a standard deviation of 3.27%, (c) center high

with a standard deviation of 2.93% and (d) center high with a standard deviation of about 4%. Thus, only a small improvement in uniformity was realized for a relatively high D.C. current applied to the electromagnet assembly 4430.

5 Next, a series of etch processes was carried out under similar conditions, except that 1800 Watts was applied to each of the orthogonal tubes 150-1, 150-2. The electromagnet coil current was increased in six steps of (a) zero amperes, (b) 2 amperes, (c) 3 amperes, (d) 4 amperes,  
10 (e) 5 amperes and (f) 6 amperes. The etch rate distribution was, respectively, (a) center low with a standard deviation of 1.2%, (b) center low with a standard deviation of 1.56%, (c) center high with a standard deviation of 1.73%, (d) center high with a standard deviation of 2.2%, (e) center  
15 high with a standard deviation of 2.85% and (f) center high with a standard deviation of 4.25%. Obviously the most uniform distribution lies somewhere between 2 and 3 amperes where the transition from center low to center high was made. Far greater changes in plasma distribution were made  
20 using much smaller coil current with much smaller changes in coil current. Thus, the presence of the reentrant torroidal plasma currents appears to enhance the effects of the magnetic field of the electromagnet assembly 4430. Such enhancement may extend from the increase in bias power that  
25 is possible when the torroidal plasma source is activated. In its absence, the plasma is less conductive and the plasma sheath is much thicker, so that the bias RF power applied to the wafer pedestal must necessarily be limited. When the torroidal plasma source is activated (e.g., at 1800 Watts  
30 for each of the two orthogonal tubes 150-1, 150-2) the plasma is more conductive, the plasma sheath is thinner and more bias power can be applied. As stated before herein, the effect of the D.C. magnetic field may be dependent upon the interaction between the D.C. magnetic field and the  
35 electric field of the plasma sheath, which in turn depends upon the RF bias power applied to the pedestal. Furthermore,



the reentrant torroidal plasma currents may be attracted to the central plasma region due to the aforementioned postulated interaction between D.C. magnetic field and the electric field of the plasma sheath, further enhancing the plasma ion density in that region.

The effects of the port-to-port separation distance S of FIG. 55A were explored in another series of etch processes on blanket oxide wafers. The same etch process was carried out in reactors having separation distances S of 16.5 inches and 20.5 inches respectively. The etch rate in the one with smaller separation distance was 31% greater than in the one with the greater separation distance (i.e., 6993 vs 5332 Angstroms/minute) with 1800 Watts applied to each one of the orthogonal tubes 150-1, 150-2 with zero current applied to the electromagnet assembly 4300 in each reactor.

The effects of the port-to-port separation distance S of FIGS. 55-56 were also explored in another series of etch processes on oxide wafers patterned with photoresist. With 3.7 amperes applied to the electromagnet assembly 4300 having the smaller source (16.5 inch) separation distance S, the etch rate was 10450 Angstroms/minute vs 7858 Angstroms/minute using the larger source (20.5 inch) separation distance S. The effect of increasing power in the reactor having the greater (20.5 inches) separation distance S was explored. Specifically, the same etch process was carried out in that reactor with source power applied to each of the orthogonal tubes 150-1, 150-2 being 1800 Watts and then at 2700 Watts. The etch rate increased proportionately very little, i.e., from 7858 Angstroms/minute to 8520 Angstroms/minute. Thus, the effect of the port-to-port separation distance S on plasma ion density and etch rate cannot readily be compensated by changing plasma source power. This illustrates the

importance of cases such as the case of FIGS. 65A, 65B and 66 in which a relatively short port-to-port separation distance S is accommodated while in effect lengthening the distance over which the plasma current is permitted to equilibrate after being split by the triangular splitters 5440.

The pole piece 4440 has been disclosed as being either a permanent magnet or the core of an electromagnet surrounded by a coil 4450. However, the pole piece 4440 may be eliminated, leaving only the coil 4450 as an air coil inductor that produces a magnetic field having a similar orientation to that produced by the pole piece 4440. The air coil inductor 4450 may thus replace the pole piece 4440. Therefore, in more general terms, what is required to produce the requisite radial magnetic field is an elongate pole-defining member which may be either the pole piece 4440 or an air coil inductor 4450 without the pole piece 4440 or the combination of the two. The diameter of the pole-defining member is relatively narrow to appropriately confine the peak of the radial magnetic field.

#### Plasma Immersion Ion Implantation:

Referring to FIG. 79, a plasma immersion ion implantation reactor in accordance with one aspect of the invention includes a vacuum chamber 8010 having a ceiling 8015 supported on an annular side wall 8020. A wafer support pedestal 8025 supports a semiconductor (e.g., silicon) wafer or workpiece 8030. A vacuum pump 8035 is coupled to a pumping annulus 8040 defined between the pedestal 8025 and the side wall 8020. A butterfly valve 8037 regulates gas flow into the intake of the pump 8035 and controls the chamber pressure. A gas supply 8045 furnishes process gas containing a dopant impurity into the chamber 8010 via a system of gas injection ports that includes the

injection port 8048 shown in the drawing. For example, if the wafer 8030 is a crystalline silicon wafer a portion of which is to be implanted with a p-type conductivity dopant impurity, then the gas supply 8045 may furnish  $\text{BF}_3$  and/or  $\text{B}_2\text{H}_6$  gas into the chamber 8010, where Boron is the dopant impurity species. Generally, the dopant-containing gas is a chemical consisting of the dopant impurity, such as boron (a p-type conductivity impurity in silicon) or phosphorus (an n-type conductivity impurity in silicon) and a volatile species such as fluorine and/or hydrogen. Thus, fluorides and/or hydrides of boron, phosphorous or other dopant species such as arsenic, antimony, etc., can be dopant gases. In a plasma containing a fluoride and/or hydride of a dopant gas such as  $\text{BF}_3$ , there is a distribution of various ion species, such as  $\text{BF}_2^+$ ,  $\text{BF}^+$ ,  $\text{B}^+$ ,  $\text{F}^+$ ,  $\text{F}^-$  and others (such as inert additives). All types of species may be accelerated across the sheath and may implant into the wafer surface. The dopant atoms (e.g., boron or phosphorous atoms) typically dissociate from the volatile species atoms (e.g., fluorine or hydrogen atoms) upon impact with the wafer at sufficiently high energy. Although both the dopant ions and volatile species ions are accelerated into the wafer surface, some portion of the volatile species atoms tend to leave the wafer during the annealing process that follows the ion implantation step, leaving the dopant atoms implanted in the wafer.

A plasma is generated from the dopant-containing gas within the chamber 8010 by an inductive RF power applicator including an overhead coil antenna 8050 coupled to an RF plasma source power generator 8055 through an impedance match circuit 8060. An RF bias voltage is applied to the wafer 8030 by an RF plasma bias power generator 8065 coupled to the wafer support pedestal 8025 through an impedance match circuit 8070. A radially outer coil antenna 8052 may be driven independently by a second RF plasma source power

generator 8057 through an impedance match circuit 8062.

The RF bias voltage on the wafer 8030 accelerates ions from the plasma across the plasma sheath and into the wafer surface, where they are lodged in generally interstitial sites in the wafer crystal structure. The ion energy, ion mass, ion flux density and total dose may be sufficient to amorphize (damage) the structure of the wafer. The mass and kinetic energy of the dopant (e.g., boron) ions at the wafer surface and the structure of the surface itself determine the depth of the dopant ions below the wafer surface. This is controlled by the magnitude of the RF bias voltage applied to the wafer support pedestal 8025. After the ion implantation process is carried out, the wafer is subjected to an anneal process that causes the implanted dopant atoms to move into substitutional atomic sites in the wafer crystal. The substrate surface may not be crystalline if it has been pre-amorphized prior to the plasma immersion ion implant process, or if the ion energy, ion mass, ion flux density and total dose of plasma immersion ion implant process itself is sufficient to amorphize the structure of the wafer. In such a case, the anneal process causes the amorphous (damaged) layer to recrystallize with the incorporation and activation of implanted dopant. The conductance of the implanted region of the semiconductor is determined by the junction depth and the volume concentration of the activated implanted dopant species after the subsequent anneal process. If, for example, a p-type conductivity dopant such as boron is implanted into a silicon crystal which has been previously doped with an n-type dopant impurity, then a p-n junction is formed along the boundaries of the newly implanted p-type conductivity region, the depth of the p-n junction being the activated implanted depth of the p-type dopant impurities after anneal. The junction depth is determined by the bias voltage on the wafer (and by the anneal process), which is

controlled by the power level of the RF plasma bias power generator 8065. The dopant concentration in the implanted region is determined by the dopant ion flux ("dose") at the wafer surface during implantation and the duration of the ion flux. The dopant ion flux is determined by the magnitude of the RF power radiated by the inductive RF power applicator 8050, which is controlled by the RF plasma source power generator 8055. This arrangement enables independent control of the time of implant, the conductivity of the implanted region and the junction depth. Generally, the control parameters such as the power output levels of the bias power RF generator 8065 and the source power RF generator 8055 are chosen to minimize the implant time while meeting the target values for conductivity and junction depth. For more direct control of ion energy, the bias generator may have "voltage" rather than "power" as its output control variable.

An advantage of the inductive RF plasma source power applicator 8050 is that the ion flux (the dopant dose rate) can be increased by increasing the power level of the RF source power generator 8055 without a concomitant increase in plasma potential. The bias voltage level is controlled by the RF bias power generator at a preselected value (selected for the desired implant depth) while the inductive RF source power is increased to increase the ion flux (the dopant dose rate) without significantly increasing the plasma potential. This feature minimizes contamination due to sputtering or etching of chamber surfaces. It further reduces the consumption of consumable components within the chamber that wear out over time due to plasma sputtering. Since the plasma potential is not necessarily increased with ion flux, the minimum implant energy is not limited (increased), thereby allowing the user to select a shallower junction depth than would otherwise have been possible. In contrast, it will be recalled that the microwave ECR plasma

source was characterized by a relatively high minimum plasma potential, which therefore limited the minimum implant energy and therefore limited the minimum junction depth.

5       An advantage of applying an RF bias voltage to the wafer (instead of a D.C. bias voltage) is that it is far more efficient (and therefore more productive) for ion implantation, provided the RF bias frequency is suitably chosen. This is illustrated in FIGS. 80A, 80B and 80C.

10   FIG. 80A illustrates a one-millisecond D.C. pulse applied to the wafer in conventional practice, while FIG. 80B illustrates the resulting ion energy at the wafer surface. The D.C. pulse voltage of FIG. 80A is near the target bias voltage at which ions become substitutional upon annealing

15   at the desired implant junction depth. FIG. 80B shows how the ion energy decays from the initial value corresponding to the voltage of the pulse of FIG. 80A, due to resistive-capacitive effects at the wafer surface. As a result, only about the first micro-second (or less) of the one-

20   millisecond D.C. pulse of FIG. 80A is actually useful, because it is only this micro-second portion of the pulse that produces ion energies capable of implanting ions that become substitutional (during annealing) at the desired junction depth. The initial (one microsecond) period of the

25   D.C. pulse may be referred to as the RC time. During the remaining portion of the D.C. pulse, ions fail to attain sufficient energy to reach the desired depth or to become substitutional upon annealing, and may fail to penetrate the wafer surface so as to accumulate in a deposited film that

30   resists further implantation. This problem cannot be solved by increasing the pulse voltage, since this would produce a large number of ions that would be implanted deeper than the desired junction depth. Thus, ions are implanted down to the desired junction depth during only about a tenth of a

35   percent of the time. This increases the time required to reach the target implant density at the desired junction

depth. The resulting spread in energy also reduces the abruptness of the junction. In contrast, each RF cycle in a 1 millisecond burst of a 1 MHz RF bias voltage illustrated in FIG. 80C has an RF cycle time not exceeding the so-called  
5 RC time of FIG. 80B. As a result, resistive-capacitive effects encountered with a pulsed D.C. bias voltage are generally avoided with an RF bias voltage of a sufficient frequency. Therefore, ions are implanted down to the desired junction depth during a far greater percentage of  
10 the time of the 1 MHz RF bias voltage of FIG. 80C. This reduces the amount of time required to reach a target implant density at the desired junction depth. Thus, the use of an RF bias voltage on the wafer results in far greater efficiency and productivity than a D.C. pulse  
15 voltage, depending upon the choice of RF frequency.

The frequency of the RF bias is chosen to satisfy the following criteria: The RF bias frequency must be sufficiently high to have a negligible voltage drop across  
20 the pedestal (cathode) dielectric layers) and minimize sensitivity to dielectric films on the backside or front side of the wafer and minimize sensitivity to chamber wall surface conditions or deposition of plasma by-products. Moreover, the frequency must be sufficiently high to have a  
25 cycle time not significantly exceeding the initial period (e.g., one micro-second) before resistive-capacitive (RC) effects reduce ion energy more than 2% below the target energy, as discussed immediately above. Furthermore, the RF bias frequency must be sufficiently high to couple across  
30 insulating capacitances such as films on the wafer surface, dielectric layers on the wafer support pedestal, coatings on the chamber walls, or deposited films on the chamber walls. (An advantage of RF coupling of the bias voltage to the wafer is that such coupling does not rely upon ohmic contact  
35 and is less affected by changes or variations in the surface conditions existing between the wafer and the support

pedestal.) However, the RF bias frequency should be sufficiently low so as to not generate significant plasma sheath oscillations (leaving that task to the plasma source power applicator). More importantly, the RF bias frequency should be sufficiently low for the ions to respond to the oscillations of the electric field in the plasma sheath overlying the wafer surface. The considerations underlying this last requirement are now discussed with reference to FIGS. 81A through 81D.

10

FIG. 81A illustrates the plasma ion saturation current at the wafer surface as a function of D.C. bias voltage applied to the wafer, the current being greatest (skewed toward) the higher voltage region. FIG. 81B illustrates the oscillation of the RF voltage of FIG. 80C. The asymmetry of the ion saturation current illustrated in FIG. 80A causes the ion energy distribution created by the RF bias voltage of FIG. 80B to be skewed in like manner toward the higher energy region, as illustrated in FIG. 80C. The ion energy distribution is concentrated most around an energy corresponding to the peak-to-peak voltage of the RF bias on the wafer. But this is true only if the RF bias frequency is sufficiently low for ions to follow the oscillations of the electric field in the plasma sheath. This frequency is generally a low frequency around 100 kHz to 3 MHz, but depends on sheath thickness and charge-to-mass ratio of the ion. Sheath thickness is a function of plasma electron density at the sheath edge and sheath voltage. Referring to FIG. 81D, as this frequency is increased from the low frequency (denoted F1 in FIG. 81D) to a medium frequency (denoted F2 in FIG. 81D) and finally to a high frequency such as 13 MHz (denoted F3 in FIG. 81D), the ability of the ions to follow the plasma sheath electric field oscillation is diminished, so that the energy distribution is narrower. At the HF frequency (F3) of FIG. 81D, the ions do not follow the sheath electric field oscillations, and instead



achieve an energy corresponding to the average voltage of the RF bias voltage, i.e., about half the RF bias peak-to-peak voltage. As a result, the ion energy is cut in half as the RF bias frequency increases to an HF frequency (for a  
5 constant RF bias voltage). Furthermore, at the medium frequency, we have found that the plasma behavior is unstable in that it changes sporadically between the low frequency behavior (at which the ions have an energy corresponding to the peak-to-peak RF bias voltage) and the  
10 high frequency behavior (at which the ions have an energy corresponding to about half the peak-to-peak RF bias voltage). Therefore, by maintaining the RF bias frequency at a frequency that is sufficiently low (corresponding to the frequency F1 of FIG. 81D) for the ions to follow the  
15 plasma sheath electric field oscillations, the RF bias peak-to-peak voltage required to meet a particular ion implant depth requirement is reduced by a factor of nearly two, relative to behavior at a medium frequency (F2) or a high frequency (F3). This is a significant advantage because  
20 such a reduction in the required RF bias voltage (e.g., by a factor of two) greatly reduces the risk of high voltage arcing in the wafer support pedestal and the risk of damaging thin film structures on the wafer. This is particularly important because in at least a particular  
25 plasma immersion ion implantation source described later in this specification, ion energies match those obtained in a conventional ion beam implanter, provided the plasma RF bias voltage is twice the acceleration voltage of the conventional ion beam implanter. Thus, at a high frequency  
30 plasma RF bias voltage, where ion energies tend to be half those obtained at low frequency, the required plasma RF bias voltage is four times the acceleration voltage of the conventional ion beam implanter for a given ion energy level. Therefore, it is important in a plasma immersion ion  
35 implantation reactor to exploit the advantages of a low frequency RF bias voltage, to avoid the necessity of

excessive RF bias voltages.

Good results are therefore attained by restricting the RF bias power frequency to a low frequency range between 10 kHz and 10 MHz. Better results are obtained by limiting the RF bias power frequency to a narrower range of 50 kHz to 5 MHz. The best results are obtained in the even narrower bias power frequency range of 100 kHz to 3 MHz. We have found optimum results at about 2 MHz plus or minus 5%.

Both the RF source power generator 8055 and the RF bias power generator 8065 may apply continuous RF power to the inductive power applicator 8050 and the wafer pedestal 8025 respectively. However, either or both of the generators 8055, 8065 may be operated in burst modes controlled by a controller 8075. The controller 8075 may also control the generator 8057 in a burst mode as well if the outer coil antenna 8052 is present. Operation in an implementation not including the outer coil antenna 8057 will now be described. The RF signals produced by each of the generators 8055, 8065 may be pulse modulated to produce continuous wave (CW) RF power in bursts lasting, for example, one millisecond with a repetition rate on the order of 0.5 kHz, for example. Either one or both of the RF power generators 8055, 8065 may be operated in this manner. If both are operated in such a burst mode simultaneously, then they may be operated in a push-pull mode, or in an in-synchronism mode, or in a symmetrical mode or in a non-symmetrical mode, as will now be described.

A push-pull mode is illustrated in the contemporaneous time domain waveforms of FIGS. 82A and 82B, illustrating the RF power waveforms of the respective RF generators 8055 and 8065, in which the bursts of RF energy from the two generators 8055, 8065 occur during alternate time windows. FIGS. 82A and 82B illustrate the RF power waveforms of the

generators 8055 and 8065, respectively, or vice versa.

An in-synchronism mode is illustrated in the contemporaneous time domain waveforms of FIGS. 82C and 82D, in which the bursts of RF energy from the two generators 8055, 8065 are simultaneous. They may not be necessarily in phase, however, particularly where the two generators 8055, 8065 produce different RF frequencies. For example, the RF plasma source power generator 8055 may have a frequency of about 13 MHz while the RF plasma bias power generator 8065 may have a frequency of about 2 MHz. FIGS. 82C and 82D illustrate the RF power waveforms of the generators 8055 and 8065, respectively, or vice versa.

In the foregoing examples, the pulse widths and pulse repetition rates of the two RF generators 8055, 8065 may be at least nearly the same. However, if they are different, then the temporal relationship between the bursts of the two generators 8055, 8065 must be selected. In the example of the contemporaneous time domain waveforms of FIGS. 82E and 82F, one of the generators 8055, 8065 produces shorter RF bursts illustrated in FIG. 82F while the other produces longer RF bursts illustrated in FIG. 82E. In this example, the bursts of the two generators 8055, 8065 are symmetrically arranged, with the shorter bursts of FIG. 82F centered with respect to the corresponding longer bursts of FIG. 82E. FIGS. 82E and 82F illustrate the RF power waveforms of the generators 8055 and 8065, respectively, or vice versa.

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In another example, illustrated in the contemporaneous time domain waveforms of FIGS. 82G and 82H, the shorter bursts (FIG. 82H) are not centered relative to the corresponding longer bursts (FIG. 82G), so that they are asymmetrically arranged. Specifically, in this example the shorter RF bursts of FIG. 82H coincide with the later

portions of corresponding ones of the long bursts of FIG. 82G. Alternatively, as indicated in dashed line in FIG. 82H, the short RF bursts of FIG. 82H may instead coincide with the earlier portions of corresponding ones of the long RF bursts of FIG. 82G. FIGS. 82G and 82H illustrate the RF power waveforms of the generators 8055 and 8065, respectively, or vice versa.

The inductive RF source power applicator 8050 of FIG. 79 tends to exhibit a rapid increase in dissociation of fluorine-containing species in the plasma as plasma source power (and ion flux) is increased, causing undue etching of semiconductor films on the wafer during the implantation process. Such etching is undesirable. A plasma immersion ion implantation reactor that tends to avoid this problem is illustrated in FIG. 83A. The plasma immersion ion implantation reactor of FIG. 83A has a capacitive source power applicator constituting a conductive (metal) or semiconducting ceiling 8015' electrically insulated from the grounded side wall 8020 by an insulating ring 8017. Alternatively, the ceiling may be metal, conductive, or semiconducting and be coating by an insulating, conducting or semiconducting layer. The RF plasma source power generator 8055 drives the ceiling 8015' through the impedance match circuit 8060 in the manner of a capacitive plate. Plasma is generated by oscillations in the plasma sheath produced by the RF power capacitively coupled from the ceiling 8015'. In order to enhance such plasma generation, the frequency of the plasma RF source power generator 8055 is relatively high, for example within the very high frequency (VHF) range or 30 MHz and above. The wafer pedestal 8025 may serve as a counter electrode to the ceiling 8015'. The ceiling 8015' may serve as a counter electrode to the RF bias voltage applied to the wafer pedestal 8025. Alternatively, the chamber wall may serve as

a counter electrode to either or both wafer bias and ceiling bias voltages. In one implementation, the dopant-containing gas is fed through the ceiling 8015' through plural gas injection orifices 8048'.

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The capacitively coupled plasma ion immersion implantation reactor of FIG. 83A enjoys the advantages of the inductively coupled reactor of FIG. 79 in that both types of reactors permit the independent adjustment of ion flux (by adjusting power level of the plasma source power generator 8055) and of the ion energy or implant depth (by adjusting the power level of the plasma bias power generator 8065). In addition, when plasma source power or ion flux is increased, the capacitively coupled plasma ion immersion reactor of FIG. 83A exhibits a smaller increase in dissociation of fluorine-containing species in the gas fed from the dopant gas supply 8045 and a smaller increase in reaction by-products which would otherwise lead to excessive etch or deposition problems. The advantage is that ion flux may be increased more freely without causing an unacceptable level of etching or deposition during ion implantation.

The higher frequency RF power of the plasma source power generator 8055 controls plasma density and therefore ion flux at the wafer surface, but does not greatly affect sheath voltage or ion energy. The lower frequency RF power of the bias power generator 8065 controls the sheath voltage and therefore the ion implantation energy and (junction) depth and does not contribute greatly to ion generation or ion flux. The higher the frequency of the plasma source power generator, the less source power is wasted in heating ions in the plasma sheath, so that more of the power is used to generate plasma ions through oscillations of the plasma sheath or by heating electrons in the bulk plasma. The lower frequency of the RF bias power generator 8065 is less than 10 MHz while the higher frequency of the RF plasma

source power generator 8055 is greater than 10 MHz. More preferably, the lower frequency is less than 5 MHz while the higher frequency is greater than 15 MHz. Even better results are obtained with the lower frequency being less than 3 MHz and the higher frequency exceeding 30 MHz or even 50 MHz. In some cases the source power frequency may be as high as 160 MHz or over 200 MHz. The greater the separation in frequency between the higher and lower frequencies of the source and bias power generators 8055, 8065, respectively, the more the plasma ion implant flux and the plasma ion implant energy can be separately controlled by the two generators 8055, 8065.

In the variation illustrated in FIG. 83B, the RF plasma source power generator 8055 is coupled to the wafer pedestal rather than being coupled to the ceiling 8015'. An advantage of this feature is that the ceiling 8015' is consumed (by plasma sputtering or etching) at a much lower rate than in the reactor of FIG. 83A, resulting in less wear and less metallic contamination of the plasma. A disadvantage is that isolation between the two RF generators 8055, 8065 from each other is inferior compared to the reactor of FIG. 83A, as they are both connected to the same electrode, so that control of ion flux and ion energy is not as independent as in the reactor of FIG. 83A.

In either of the reactors of FIGS. 83A or 83B, the controller 8075 can operate in the manner described above with reference to FIGS. 82A through 82H, in which the respective RF power waveforms applied to the ceiling 8015' and the pedestal 8025 are in a push-pull mode (FIGS. 82A and B), or an in-synchronism mode (FIGS. 82C and D), or a symmetric mode (FIGS. 802E and F) or a non-symmetric mode (FIGS. 82G and H).

FIGS. 83A and 83B show that the RF source power

generator 8055 can drive the ceiling 8015' (FIG. 83A) with the side wall 8020 and/or the wafer support pedestal 8025 connected to the RF return terminal of the generator 8055, or, in the alternative, the RF source power generator 8055  
5 can drive the wafer support pedestal 8025 with the ceiling 8015' and/or the sidewall 8020 connected to the RF return terminal of the generator 8055. Thus, the RF source power generator is connected across the wafer support pedestal 8025 and the sidewall 8020 or the ceiling 8015' (or both).  
10 The polarity of the connections to the source power generator 8055 may be reversed, so that it drives the side wall 8020 and/or ceiling 8015' with the pedestal 8025 being connected to the RF return terminal of the generator 8055.

15 As set forth above, the plasma immersion ion implantation inductively coupled reactor of FIG. 79 has distinct advantages, including (a) the capability of a large ion flux/high plasma ion density, (b) independently controlled ion energy, and (c) low minimum ion energy  
20 (plasma potential). The plasma immersion ion implantation capacitively coupled reactor of FIG. 83A has the additional advantage of having more controllable dissociation of process gases and reactive byproducts as ion flux is increased, than the inductively coupled reactor of FIG. 79.  
25 However, the capacitively coupled reactor of FIG. 83A has a higher minimum ion energy/plasma potential than the inductively coupled reactor of FIG. 79. Thus, these two types of reactors provide distinct advantages, but neither provides all of the advantages.

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A plasma immersion ion implantation reactor that provides all of the foregoing advantages, including low minimum ion energy and low process gas dissociation, is illustrated in FIG. 84. In FIG. 84, the inductively or  
35 capacitively coupled plasma sources of FIG. 79 or 83A are replaced by a torroidal plasma source of the type disclosed

above in FIGS. 1-78. In the basic configuration of FIG. 84, the torroidal plasma source includes a reentrant hollow conduit 8150 over the ceiling 8015, corresponding to the conduit 150 of FIG. 1. The conduit 8150 of FIG. 84 has one  
5 open end 8150a sealed around a first opening 8155 in the ceiling 8015 and an opposite open end 8150b sealed around a second opening 8160 in the ceiling 8015. The two openings or ports 8155, 8160 are located in the ceiling over opposite sides of the wafer support pedestal 8025. While FIG. 84  
10 illustrates the openings 8155, 8160 being in the ceiling, the openings could instead be in the base or floor of the chamber, as in FIG. 12, or in the side wall of the chamber, as in FIG. 26, so that the conduit 8150 may pass over or under the chamber. RF plasma source power is coupled from  
15 the RF generator 8055 through the optional impedance match circuit 8060 to the reentrant conduit by an RF plasma source power applicator 8110. Various types of source power applicators for a reentrant hollow conduit are disclosed in FIGS. 1-78, any one of which may be employed in the plasma  
20 immersion ion implantation reactor of FIG. 84. In the implementation illustrated in FIG. 84, the RF plasma source power applicator 8110 is similar to that illustrated in FIG. 13, in which a magnetically permeable core 8115 having a torus shape surrounds an annular portion of the conduit  
25 8150. The RF generator 8055 is coupled through the optional impedance match circuit to a conductive winding 8120 around the magnetic core 8115. An optional tuning capacitor 8122 may be connected across the winding 8120. The RF generator 8055 may be frequency-tuned to maintain an impedance match,  
30 so that the impedance match circuit 8060 may not be necessary.

The reactor chamber includes the process region 8140 between the wafer support pedestal 8025 and the ceiling  
35 8015. The gas supply 8045 furnishes dopant gases into the reactor chamber 8140 through gas injection orifices 8048 in



the ceiling 8015. Plasma circulates (oscillates) through the reentrant conduit 8150 and across the process region 8140 in response to the RF source power coupled by the source power applicator 8110. As in the reactor of FIG. 13, the reentrant conduit 8150 is formed of a conductive material and has a narrow gap or annular break 8152 filled with an insulator 8154. The dopant gases furnished by the gas supply 8045 contain a species that is either a donor (N-type) or acceptor (P-type) impurity when substituted into the semiconductor crystal structure of the wafer 8030. For example, if the wafer is a silicon crystal, then an N-type dopant impurity may be arsenic or phosphorous, for example, while a P-type dopant impurity may be boron, for example. The dopant gas furnished by the gas supply 8045 is a chemical combination of the dopant impurity with an at-least partially volatile species, such as fluorine for example. For example, if a P-type conductivity region is to be formed by ion implantation, then the dopant gas may be a combination of boron and fluorine, such as  $\text{BF}_3$ , for example. Or, for example, the dopant gas be a hydride, such as  $\text{B}_2\text{H}_6$ . Phosphorous doping may be accomplished using a fluoride such as  $\text{PF}_3$  or  $\text{PF}_5$  or a hydride such as  $\text{PH}_3$ . Arsenic doping may be accomplished using a fluoride such as  $\text{AsF}_5$  or a hydride such as  $\text{AsH}_3$ .

The RF bias power generator provides an RF bias voltage, with the RF bias frequency selected as described above with reference to FIG. 81D. Good results are attained by restricting the RF bias power frequency to a low frequency range between 10 kHz and 10 MHz. Better results are obtained by limiting the RF bias power frequency to a narrower range of 50 kHz to 5 MHz. The best results are obtained in the even narrower bias power frequency range of 100 kHz to 3 MHz. We have found optimum results at about 2 MHz plus or minus 5%.

In the reactor of FIG. 84, both the RF source power generator 8055 and the RF bias power generator 8065 may apply continuous RF power to the inductive power applicator 8110 and the wafer pedestal 8025 respectively. However, 5 either or both of the generators 8055, 8065 may be operated in burst modes controlled by a controller 8075. The RF signals produced by each of the generators 8055, 8065 may be pulse modulated to produce continuous wave (CW) RF power in bursts lasting, for example, one millisecond with a 10 repetition rate on the order of 0.5 kHz, for example. Either one or both of the RF power generators 8055, 8065 may be operated in this manner. If both are operated in such a burst mode simultaneously, then they may be operated in a push-pull mode, or in an in-synchronism mode, or in a 15 symmetrical mode or in a non-symmetrical mode, as will now be described for the reactor of FIG. 84.

A push-pull mode is illustrated in the contemporaneous time domain waveforms of FIGS. 82A and 82B, illustrating the 20 RF power waveforms of the respective RF generators 8055 and 8065, in which the bursts of RF energy from the two generators 8055, 8065 occur during alternate time windows. FIGS. 82A and 82B illustrate the RF power waveforms of the generators 8055 and 8065, respectively, or vice versa.

25 An in-synchronism mode is illustrated in the contemporaneous time domain waveforms of FIGS. 82C and 82D, in which the bursts of RF energy from the two generators 8055, 8065 are simultaneous. They may not be necessarily in 30 phase, however, particularly where the two generators 8055, 8065 produce different RF frequencies. For example, the RF plasma source power generator 8055 may have a frequency of about 13 MHz while the RF plasma bias power generator 8065 may have a frequency of about 2 MHz. FIGS. 82C and 82D 35 illustrate the RF power waveforms of the generators 8055 and 8065, respectively, or vice versa.

In the foregoing examples, the pulse widths and pulse repetition rates of the two RF generators 8055, 8065 may be at least nearly the same. However, if they are different, then the temporal relationship between the bursts of the two generators 8055, 8065 must be selected. In the example of the contemporaneous time domain waveforms of FIGS. 82E and 82F, one of the generators 8055, 8065 produces shorter RF bursts illustrated in FIG. 82F while the other produces longer RF bursts illustrated in FIG. 82E. In this example, the bursts of the two generators 8055, 8065 are symmetrically arranged, with the shorter bursts of FIG. 82F centered with respect to the corresponding longer bursts of FIG. 82E. FIGS. 82E and 82F illustrate the RF power waveforms of the generators 8055 and 8065, respectively, or vice versa.

In another example, illustrated in the contemporaneous time domain waveforms of FIGS. 82G and 82H, the shorter bursts (FIG. 82H) are not centered relative to the corresponding longer bursts (FIG. 82G), so that they are asymmetrically arranged. Specifically, in this example the shorter RF bursts of FIG. 82H coincide with the later portions of corresponding ones of the long bursts of FIG. 82G. Alternatively, as indicated in dashed line in FIG. 82H, the short RF bursts of FIG. 82H may instead coincide with the earlier portions of corresponding ones of the long RF bursts of FIG. 82G. FIGS. 82G and 82H illustrate the RF power waveforms of the generators 8055 and 8065, respectively, or vice versa.

The torroidal plasma immersion ion implantation reactor of FIG. 84 can be operated with a pulsed D.C. bias voltage instead of an RF bias voltage. In this case, the bias power generator 8065 would be D.C. source rather than an RF source. Thus, in the different operational modes of FIGS.

82A through 82H discussed above, the pulsed RF bias voltage may be replaced by a pulsed D.C. bias voltage of the same pulse width, with only the source power generator 8055 producing an RF power burst.

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FIG. 85 illustrates a modification of the plasma immersion ion implantation reactor of FIG. 84 having a second reentrant conduit 8151 crossing the first reentrant conduit 8150, in a manner similar to the reactor of FIG. 44. Plasma power is coupled to the second conduit 8151 from a second RF plasma source power generator 8056 through a second optional match circuit 8061 to a second source power applicator 8111 that includes a second magnetically permeable core 8116 and a second core winding 8121 driven by the second RF source power generator 8056. Process gas from the gas supply 8045 may be introduced into the chamber by a gas distribution plate or showerhead incorporated in the ceiling 8015 (as in the gas distribution plate 210 of FIG. 44). However, the plasma immersion ion implantation reactor of FIG. 85 is greatly simplified by using a small number of process gas injectors 8048 in the ceiling 8015 or in the side wall 8020 or elsewhere, such as in the base of the chamber (not shown) coupled to the dopant gas supply, rather than a showerhead. Moreover, the gap between the ceiling 8015 and the wafer pedestal 8025 may be relatively large (e.g., two to six inches) and a gas distribution plate eliminated in favor of discrete gas injectors or diffuser 8048 in the ceiling 8015 or gas injectors or diffusers 8049 in the side wall 8020 because there is no need to generate plasma close to the wafer surface. The gas injectors or diffusers 8049 may be joined in a ring 8049 on the side wall 8020. Generally, the higher the maximum implant depth and ion energy requirement, the greater the gap between ceiling and wafer that is required. For example, for a peak-to-peak RF bias voltage of 10 kV, a gap of 4 inches is preferable over a 2 inch gap for best plasma uniformity across a wide

range of gas species and plasma electron densities. The term diffuser is employed in the conventional sense as referring to a type of gas distribution device having a wide angle of gas flow distribution emanating from the device.

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FIG. 86 is a plan view of the interior surface of the ceiling 8015, showing one arrangement of the gas injection orifices 8048, in which there is one central orifice 8048-1 in the center of the ceiling 8015 and four radially outer orifices 8048-2 through 8048-5 uniformly spaced at an outer radius. FIG. 87 illustrates how the dopant gas supply 8045 may be implemented as a gas distribution panel. The gas distribution panel or supply 8045 of FIG. 87 has separate gas reservoirs 8210-1 through 8210-11 containing different dopant-containing gases including fluorides of boron, hydrides of boron, fluorides of phosphorous and hydrides of phosphorous. In addition, there are gas reservoirs for other gases used in co-implantation (hydrogen and helium), material enhancement (nitrogen), surface passivation or co-implantation (fluorides of silicon or germanium or carbon).

In addition, the center orifice 8048-1 may be coupled to a reservoir oxygen gas, for use in photoresist removal and/or chamber cleaning. A control panel 8220 includes valves 8222 controlling gas flow from the respective reservoirs 8210 to the gas injection orifices. Preferably, the gases are mixed at or near the orifices, although a gas manifold 8230 may be provided to distribute the selected gases among the outer gas injection orifices 8048-2 through 8048-5. Alternatively, process gas may be injected at one or more locations in the sidewall 8020, using the nozzles 8049 of FIG. 85 or diffusers. Figure 85 shows gas injectors 8049 located around the chamber sidewalls 8020 which inject gas radially inward. Gas may be injected parallel to the ceiling and/or wafer, or may be injected with some component toward ceiling and/or wafer. For some applications, it is advantageous to utilize multiple separate gas plenums, each with its own nozzle

array. This can permit the use of chemistries which should not be combined except under vacuum, or may permit having several gas zones for neutral uniformity tuning. For this purpose, referring again to FIG. 85, a first ring 8049a  
5 joining a first set of side wall injectors 8049c serves as a first plenum, while a second ring 8049b joining a second separate set of side wall injectors 8049d serves as a second plenum. The two rings or plenums 8049a, 8049b are supplied by separate respective sets of valves 8222 of the gas panel  
10 of FIG. 87

FIG. 88 illustrates a modification of the plasma immersion ion implantation reactor of FIG. 85 in which a central electromagnet assembly 8430 is mounted over the  
15 center of the ceiling 8015. Like the electromagnet assembly 4430 of FIG. 44, the electromagnet assembly 8430 of FIG. 88 controls plasma ion density uniformity and includes a narrow elongate cylindrical pole piece 8440 formed of a magnetizable material such as iron or steel and a coil 8450  
20 of insulated conductive wire wrapped around the pole piece 8440. A magnetic current controller 8442 supplies an electrical current to the coil 8450. The controller 8442 controls the current through the coil 8450 so as to optimize uniformity of plasma ion density (ion flux) across the wafer  
25 surface.

FIGS. 89A and 89B are side and top views, respectively, illustrating a further modification incorporating a radially outer electromagnet assembly 8460. The outer electromagnet  
30 assembly 8460 is in the shape of a torus and overlies an annular outer region of the ceiling 8015 near the circumferential edge of the ceiling 8015 and adjacent the ports pairs 150, 160 of the conduits 8150, 8151. Referring to the cross-sectional view of FIG. 90A, the outer  
35 electromagnet assembly 8460 includes a coil 8462 consisting of plural windings of a single conductor connected to the

current controller 8442. In order to concentrate the magnetic field of the outer electromagnet assembly 8460 within the process region 8140, an overlying magnetic cover 8464 surrounding the sides and top of the coil 8462 but not  
5 the bottom of the coil 8462. The magnetic cover 8464 permits the magnetic field of the coil 8462 to extend downwardly below the ceiling into the process region 8140. Uniformity of the ion density and radial plasma flux distribution at the wafer surface is optimized by  
10 independently adjusting the currents in the inner and outer electromagnet assemblies 8430, 8460.

In order to avoid forming regions of very high plasma ion concentration near the ports 150, 160 of the two  
15 conduits 8150, 8151, individual plates 8466 of magnetically permeable material (e.g., iron or steel) are placed under the outer electromagnet assembly 8460 adjacent respective ones of the ports 150, 160. The circumferential extent of each plate 8466 is approximately equal to the width of each  
20 individual port 150, 160. FIGS. 90A, 90B and 90C are cross-sectional views taken along lines 90-90 of FIG. 89B. The distance between the plate 8466 and the bottom edge of the magnetic cover 8464 may be adjusted to control the amount of magnetic field coupled into portion of the process region  
25 near each individual one of the ports 150, 160. In FIG. 90A, the plate 8466 is in contact with the bottom edges of the cover 8464, so that the magnetic field near the corresponding port (150, 160) is almost completely confined within the enclosure defined by the cover 8464 and the plate  
30 8466. In FIG. 90B, the plate 8466 is slightly displaced from the bottom edge of the cover 8464, creating a small gap therebetween that allows a small magnetic field to enter the process region 8140 near the corresponding port (150, 160). In FIG. 90C, there is a large gap between the plate 8466 and  
35 the cover 8464, permitting a larger magnetic field to exist in the process region near the corresponding port (150,

160).

FIG. 91 illustrates how the RF plasma bias power generator 8065 may be coupled to the wafer support pedestal 8025. An inductor 8510 and a variable capacitor 8520 are connected in parallel between one side of a series capacitor 8530 and ground, the other side of the series capacitor 8530 being connected to the wafer support pedestal 8025. The output of the bias power generator 8065 is connected to a tap 8560 of the inductor 8510. The position of the tap 8560 and the capacitance of the variable capacitor 8520 are selected to provide an impedance match between the bias power generator 8065 and the plasma load at the wafer pedestal 8065. The variable capacitor 8520 may be controlled by a system controller 8525 to optimize matching. In this case, the circuit including the parallel inductor and capacitor 8510, 8520 serves as an impedance match circuit.

In order to follow variations in the plasma load impedance during processing, frequency tuning of the bias power generator 8065 may be employed, although this may not be necessary. The position of the tap 8560 may be selectable either manually or by the system controller 8525 to optimize matching. Alternatively, a capacitor (not shown) may be connected between the tap position and ground or between RF bias generator and tap point as an alternative matching circuit topology. This optional capacitor may be controlled by the system controller 8525 to optimize matching.

One problem in selecting the bias voltage level is that large ion energy can be reached only with a high bias voltage level, which typically requires high power. High power contributes to the plasma flux (ion density or dose rate), and can cause too high a dose rate, making it difficult to control the conductivity of the implanted region. One way of controlling the dose rate at such a high power is to pulse the RF bias power. However, controlling



the pulse rate and pulse width of repetitive pulses so as to achieve the required dose rate and conductivity is difficult. Part of the problem is that ion implantation at the desired junction depth is achieved only after the bias voltage has risen sufficiently (at the beginning of a pulse or RF burst) to reach a threshold voltage corresponding to the desired junction depth and ion energy. The solution to this problem is to avoid repetitive pulsing of the bias power, and instead use a single pulse of sufficient duration to complete ion implantation at the desired junction depth and conductivity in the implanted region. This is illustrated in the time domain waveform of FIG. 92. A timer can be employed to guarantee that the RF burst or pulse lasts the required duration ( $T_{\text{timer}}$ ). However, the timer must not begin until the sheath voltage has reached the threshold voltage ( $V_{\text{threshold}}$ ) at which ion implantation occurs at the required depth. Thus, FIG. 92 shows that the sheath voltage grows at the beginning of bias power RF burst ( $T_{\text{on}}$ ) until it reaches  $V_{\text{threshold}}$  after several cycles. At that point, the timer begins, and ends the RF burst at the expiration of  $T_{\text{timer}}$ , i.e., at  $T_{\text{off}}$ . The problem, therefore, is how to ascertain the time at which the sheath voltage reaches  $V_{\text{threshold}}$ , i.e., when to begin  $T_{\text{timer}}$ .

Another problem is how to ascertain the requisite power level of the bias power generator 8065 at which  $V_{\text{threshold}}$  is produced across the sheath.

FIG. 93 illustrates a control circuit for determining the bias generator power level that produces the desired sheath voltage and for determining when the target sheath voltage has been reached for beginning the RF burst timer. In the following description, the target bias voltage corresponding to a desired junction depth, has already been determined. In addition, the threshold voltage for implantation has also been determined, and the threshold

voltage may be synonymous with the target bias voltage. Finally, the duration time for applying RF bias power at the target bias voltage has already been determined. The RF bias power generator 8065 is controlled by a timer 8670 that  
5 begins counting sometime after the beginning of an RF burst and times out after a predetermined duration. A threshold comparator 8672 compares the peak-to-peak voltage as detected at the wafer pedestal 8025 by a peak detector 8674 with the desired threshold voltage 8676. The timer 8670 is  
10 enabled only when it receives an affirmative signal from an optical detector 8678 indicating that plasma is ignited within the reactor chamber. If the optical detector 8678 sends an affirmative signal, then the timer 8670 begins counting as soon as the comparator 8672 determines that the  
15 peak-to-peak bias voltage has reached the desired threshold. When the timer 8670 times out (after the predetermined duration), it turns off the output of the bias power generator, thus terminating the current burst of RF bias power. The timer 8670 and the threshold comparator 8672  
20 constitute a timer control loop 8680.

The power level of the bias power generator 8065 is controlled by a voltage control loop 8682. A process controller 8684 (or the process designer) determines the  
25 desired or "target" bias peak-to-peak voltage. This may be synonymous with the threshold voltage of 8676. A subtractor 8686 computes an error value as the difference between the actual peak bias voltage measured by the detector 8674 and the target bias voltage. A proportional integral  
30 conditioner 8688 multiplies this error value by a constant of proportionality,  $k$ , and integrates the error value with prior samples. The result is an estimated correction to the power level of the bias power generator 8065 that will bring the measured bias voltage closer to the target bias voltage.  
35 This estimate is superimposed on the current power level, and the result is an estimated power level command that is

applied to the power set input of the bias power generator 8065. This estimate is only valid while plasma is ignited (i.e., during an RF burst). For times between RF bursts, the bias power level is controlled in accordance with a  
5 look-up table 8690 that correlates target peak-to-peak bias voltages with estimated bias power levels. The look-up table receives the target bias voltage from the process controller 8684 and in response outputs an estimated bias power level. A pair of switches 8694, 8696 are enabled in  
10 complementary fashion by the output of the plasma ignition optical detector 8678. Thus, the switch 8694 receives the output of the sensor 8678 while the switch 8696 receives the inverted output of the sensor 8678. Thus, during an RF burst, when plasma is ignited in the chamber, the output of  
15 the proportional integral conditioner 8688 is applied to the power set input of the bias generator 8065 via the switch 8694. Between RF bursts, or when no plasma is ignited in the chamber, the output of the look-up table 8690 is applied via the switch 8696 to the power set input of the bias power  
20 generator 8065. The output of the look up table 8690 may be considered as a gross estimate that serves to initialize the RF bias power level at the beginning of each RF burst, while the output of the integral proportional conditioner is a more accurate estimate based upon actual measurement that  
25 serves to correct the bias power level during the RF burst.

One problem in the plasma immersion ion implantation reactor of FIG. 89A is that most ion implantation processes must be carried out with precise fine control over chamber  
30 pressure. This requires a relatively gradual change in chamber pressure over a given rotation of the control valve 8037 from its closed position. On the other hand, some processes, including chamber cleaning, require a very high gas flow rate (e.g., of cleaning gases) and a concomitantly  
35 high evacuation rate by the pump 8035. This requires that the vacuum control valve 8037 have a large area. The

problem is that with such a large area, a vacuum control valve does not provide the gradual change in pressure for a given rotation from its closed position that is necessary for fine control of chamber pressure during ion

5 implantation. In fact, with a large area opening and flap, the change in chamber pressure is very rapid as the flap is rotated from its closed position, so that fine control of pressure within a very low pressure range, where the flap must be nearly closed, is very difficult. This problem is

10 solved with the vacuum control valve of FIGS. 94, 95 and 96. The valve includes a flat housing 9410 having a circular opening 9412 through it. A rotatable flap 9420 having a disk shape is supported within the circular opening 9412 by a hinge 9422 attached to the housing 9410. In its closed

15 position, the flap 9420 is co-planar with the flat housing 9410. In order to prevent leakage of plasma through the valve, the gap G between the rotatable flap 9420 and the housing 9410 is narrow while the thickness T of the flap 9420 and housing 9410 is large, much greater than the gap G.

20 For example, the ratio of the thickness T to the gap G is about 10:1. This feature provides the advantage of frictionless operation. In order to provide gradual control of chamber pressure at a very low pressure range (i.e., when the flap 9420 is near its closed position), conically-shaped

25 openings 9430 are provided in the interior surface 9440 of the housing 9410 defining the edge of the opening 9412. Some of the openings 9430 have different axial locations (along the axis of the opening 9412) than others of the openings 9430. In its closed position, the flap 9420 permits

30 virtually zero gas leakage, because the openings 9430 are not exposed. As the flap 9420 begins to rotate from its closed position (i.e., in which the flap 9420 is co-planar with the housing 9410), small portions of at least some of the openings 9430 begin to be exposed, and therefore allow a

35 small amount of gas flow through the valve. As the flap 9420 continues to rotate, it exposes larger portions of the

openings 9430. Moreover, it begins to expose others of the openings 9430 not exposed during the earlier phase of its rotation due to the different axial locations of different sets of the openings 9430, so that the gas flows through  
5 more of the openings 9430 in proportion to the rotation of the flap 9420. Thus, rotation of the flap 9430 from its fully closed (co-planar) position causes a continuous but relatively gradual increase in gas flow through the openings 9430 until the bottom edge 9420a of the flap 9420 reaches  
10 the top surface 9410a of the housing 9410. At this point, all of the openings 9430 are completely exposed so that gas flow through the openings 9430 is maximum and cannot increase further. Thus, a continuous gradual increase in gas flow is achieved (and therefore one that is readily  
15 controlled with a great deal of accuracy) as the flap 9420 rotates from its fully closed position to the point at which the flap bottom edge 9420a is aligned with the housing top surface 9410a. Within this range of flap rotational position, fine gradual adjustment of a small total chamber  
20 pressure is provided. Further rotation of the flap 9420 creates an annular gap between the periphery of the flap 9420 and the periphery of the large circular opening 9412, through which gas flow increases as the flap 9420 continues to rotate.

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The plural openings 9430 in the opening interior surface 9440 are semi-circular openings that are tapered so as to increase in diameter toward the top housing surface 9410a. The tapered semi-circular openings 9430 thus define  
30 semi-conical shapes. However, other suitable shapes may be employed, such as semi-cylindrical, for example. However, one advantage of the semi-conical shape is that the rate of increase of gas flow with rotational flap position may be enhanced as the rotation progresses so that the rate  
35 continues to increase in a fairly smooth manner after the transition point at which the flap bottom edge 9420a passes

Some applications may require an RF bias voltage of over 10,000 volts. Such large voltages can cause arcing within the wafer support pedestal 8025. Such arcing distorts process conditions in the reactor. In order to enable the wafer support pedestal 8025 to withstand bias voltages as high as 10,000 volts, for example, without arcing, voids within the wafer support pedestal 8025 are filled with a dielectric filler material having a high breakdown voltage, such as Rexolite®, a product manufactured by C-Lec Plastics, Inc. As illustrated in FIG. 97, the wafer support pedestal 8025 consists of a grounded aluminum base plate 9710, an aluminum electrostatic chuck plate 9720 and a cylindrical side wall 9730. Dielectric filler material 9735 fills voids between the side wall 9730 and the electrostatic chuck plate 9720. Dielectric filler material 9737 fills voids between the electrostatic chuck plate 9720 and the base plate 9710. A coaxial RF conductor 9739 carrying the RF bias power from the RF generator 8065 (not shown in FIG. 97) is terminated in a narrow cylindrical conductive center plug 9740 that fits tightly within a matching conductive receptacle 9742 of the electrostatic chuck plate 9720. A wafer lift pin 9744 (one of three) extends through the pedestal 8025. The lift pin 9744 is tightly held within the electrostatic chuck plate 9720 by a surrounding blanket 9746 of the dielectric filler material. A void 9748 that accommodates a guide 9750 of the lift pin 9744 is located entirely within the base plate 9710 so as to minimize the risk of arcing within the void 9748. Referring to FIG. 98, bolt 9754 (one of several) holding the base plate 9710 and the electrostatic chuck plate 9720 together is completely encapsulated to eliminate any voids around the bolt 9754, with dielectric layers 9756, 9758 surrounding exposed portions of the bolt 9754. The foregoing features have been found to enable the wafer support pedestal to withstand an RF bias voltage of over 10,000 volts without experiencing arcing.

FIG. 99 illustrates an ion implantation system including a plasma immersion ion implantation reactor 9910 of the type illustrated in FIG. 79, 83A, 83B, 84, 85, 88, 89A or 93. An independent source 9920 of chamber-cleaning radicals or gases (such as fluorine-containing gases or fluorine-containing radicals like  $\text{NF}_3$  and/or other cleaning gases such as hydrogen-containing gases (e.g.,  $\text{H}_2$  or compounds of hydrogen) to produce hydrogen-containing radicals or oxygen-containing gases (e.g.,  $\text{O}_2$ ) is coupled to the implant reactor 9910 for use during chamber cleaning operations. A post-implant anneal chamber 9930 and an ion beam implanter 9940 are also included in the system of FIG. 99. In addition, an optical metrology chamber 9950 may also be included. Furthermore, a photoresist pyrolyzation chamber 9952 may be included in the system for removal of the photoresist mask subsequently after implant and prior to anneal. Alternatively, this may be accomplished within the plasma immersion implantation reactor 9910 using the RF plasma source power and optional bias power with oxygen gas, and/or by using the independent self-cleaning source with oxygen gas.

The system of FIG. 99 may also include a wet clean chamber 9956 for carrying out wafer cleaning. The wet clean chamber 9956 may employ such well known wet cleaning species as  $\text{HF}$ , for example. The wet clean chamber 9956 may be employed for pre-implantation or post-implantation cleaning of the wafer. The pre-implantation cleaning use of the wet clean chamber 9956 may be for removing a thin native oxide that can accumulate on the wafer between processing operations. The post-implantation cleaning use of the wet clean chamber 9956 may be for removing photoresist from the wafer in lieu of the photoresist strip chamber 9952. The system of FIG. 99 may further include a second, (third, fourth or more) plasma immersion ion implantation reactor

9958 of the type illustrated in FIG. 79, 83A, 83B, 84, 85, 88, 89A or 93. In one example, the first PIII reactor 9910 may be configured to ion implant a first species while the second PIII reactor 9958 may be configured to implant a  
5 second species, so that a single PIII reactor need not be re-configured to implant the two species in each wafer. Furthermore, the first and second species may be dopant impurities for opposite semiconductor conductivity types (e.g., boron and phosphorus), in which case the second PIII  
10 reactor 9958 may be employed in lieu of the beam implantation tool 9940. Or, two N-type dopants (phosphorous and arsenic) may be implanted in addition to a P-type dopant (boron), in which case boron implantation is carried out by the first PIII reactor 9910, arsenic implantation is carried  
15 out in the ion beam tool 9940 and phosphorus implantation is carried out in the second PIII reactor 9958, for example. In another example, the 2 (or more) PIII reactors may be configured to implant the same species so as to increase the throughput of the system.

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A wafer transfer robotic handler 9945 transfers wafers between the plasma ion implant reactor 9910, the anneal chamber 9930, the ion beam implanter 9940, the photoresist pyrolyzation chamber 9952, the optical metrology  
25 chamber 9950, the wet clean chamber 9956 and the second PIII reactor 9958. If the entire system of FIG. 99 is provided on a single tool or frame, the handler 9945 is a part of that tool and is supported on the same frame. However, if some of the components of the system of FIG. 99 are on  
30 separate tools located in separate places in a factory, then the handler 9945 is comprised of individual handlers within each tool or frame and a factory interface that transports wafers between tools within the factory, in the well-known manner. Thus, some or all of the components of the system  
35 of FIG. 99 may be provided on a single tool with its own wafer handler 9945. Alternatively, some or all of the



components of the system of FIG. 99 may be provided on respective tools, in which case the wafer handler 9945 includes the factory interface.

5           The process controller 8075 can receive measurements of a previously implanted wafer from the optical metrology chamber 9950, and adjust the implant process in the plasma implant reactor 9910 for later wafers. The process controller 8075 can use established data mining  
10 techniques for process correction and control. The inclusion of the ion beam implanter 9940 permits the system to perform all of the ion implantation steps required in semiconductor fabrication, including implantation of light elements (such as boron or phosphorous) by the plasma ion  
15 implant reactor 9910 and implantation of heavier elements (such as arsenic) by the ion beam implanter 9940. The system of FIG. 99 may be simplified. For example, a first version consists of only the chamber cleaning radical source 9920, the PIII reactor 9910 and the process controller 8075.  
20 A second version includes the foregoing elements of the first version and, in addition, the optical metrology tool 9950. A third version includes the foregoing elements of the second version and, in addition, the ion beam implanter 9940 and/or the second PIII reactor 9958. A fourth version  
25 includes the foregoing elements of the third version and, in addition, the anneal chamber 9930.

#### Ion Implantation Performance Of The Torroidal Source:

30           The plasma immersion ion implantation (PIII) reactor of FIG. 85 realizes many advantages not found heretofore in a single reactor. Specifically, the PIII reactor of FIG. 85 has low minimum ion implant energy (because it has a low plasma potential), low contamination (because the recirculating plasma generally does not need to interact  
35 with chamber surfaces to provide a ground return), very good control over unwanted etching (because it exhibits low

fluorine dissociation), and excellent control over ion implant flux (because it exhibits a nearly linear response of plasma electron density to source power).

5        The advantage of excellent control over ion implant flux is illustrated in the graph of FIG. 100, in which electron density is plotted as a function of source power level for the torroidal source PIII reactor of FIG. 85 and for an inductively coupled PIII reactor of the type  
10 illustrated in FIG. 79. Electron density is an indicator of plasma ion density and therefore of the ion implant flux or implant dose to the wafer. The inductively coupled source of the PIII reactor of FIG. 79 tends to have a highly non-linear response of electron density to applied source power,  
15 exhibiting a sudden increase in electron density at a threshold power level, PICP, below which the slope (response) is negligible and above which the slope (response) is so steep that electron density (and therefore ion implant flux or dose) is nearly impossible to control to  
20 any fine degree. In contrast the torroidal source PIII reactor of FIG. 85 has a generally linear and gradual response of electron density to source power level above a threshold power level PTH, so that ion implant flux (dose) is readily controlled to within a very fine accuracy even at  
25 very high source power level. It should be noted here that the plasma source power level of the torroidal source PIII reactor of FIG. 85 is a function of the two different source power generators 8055, 8056 coupled to the respective reentrant conduits 8150, 8151. The source power frequency  
30 may be about 13.56 MHz, although the frequency of each of the two source power generators 8055, 8056 are offset from this frequency (13.56 MHz) by +100 kHz and -100 kHz, respectively, so that the two torroidal plasma current paths established by the sources 8110 and 8111 are decoupled from  
35 one another by being de-tuned from one another by about 200 kHz. However, their power levels may be generally about the

same. Operating frequencies are not limited to the regime described here, and another RF frequency and frequency offset may be selected for the pair of RF source power generators 8055, 5056.

5

The advantage of low fluorine dissociation of the PIII reactor of FIG. 85 is important in preventing unwanted etching that can occur when a fluorine-containing dopant gas, such as  $\text{BF}_3$ , is employed. The problem is that if the  $\text{BF}_3$  plasma by-products are dissociated into the simpler fluorine compounds, including free fluorine, the etch rate increases uncontrollably. This problem is solved in the PIII reactor of FIG. 85 by limiting the fluorine dissociation even at high power levels and high plasma density. This advantage is illustrated in the graph of FIG. 101, in which free fluorine density (an indicator of fluorine dissociation) is plotted as a function of source power for the PIII reactor of FIG. 85 and for the inductively coupled reactor of FIG. 79 for the sake of comparison. The inductively coupled reactor of FIG. 79 exhibits an extremely sudden increase in free fluorine density above a particular source power level,  $\text{PDIS}$ , above which the dissociation increases at a very high rate of change, and is therefore difficult to control. In contrast, the PIII reactor of FIG. 85 exhibits generally linear and nearly negligible (very gradual) increase in free fluorine density above a threshold source power  $\text{PTH}$ . As a result, there is very little unwanted etching during ion implantation with fluorine-containing dopant gases in the torroidal source PIII reactor of FIG. 85. The etching is further minimized if the temperature of the wafer is held to a low temperature, such as below 100 degrees C, or more preferably below 60 degrees C, or most preferably below 20 degrees C. For this purpose, the wafer pedestal 8025 may be an electrostatic chuck that holds and releases the wafer electrostatically with thermal control cooling apparatus

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8025a and/or heating apparatus 8025b that control the temperature of a semiconductor wafer or workpiece held on the top surface of the wafer support pedestal 8025. Some small residual etching (such as may be realized with the torroidal source PIII reactor of FIG. 85) is acceptable and may actually prevent the deposition of unwanted films on the wafer during ion implantation. During ion implantation, some plasma by-products may deposit as films on the wafer surface during ion implantation. This is particularly true in cases where the implantation process is carried out at a very low ion energy (low bias voltage) and particularly with a dopant gas consisting of a hydride of the dopant species (e.g., a hydride of boron or a hydride of phosphorous). In order to further reduce unwanted depositions that normally occur with hydride dopants (e.g.,  $B_2H_6$ ,  $PH_3$ ), one aspect of the process is to add hydrogen and/or helium to the dopant gas to eliminate the deposition on the surface of the wafer. However, the requisite etch rate to compete with such an unwanted deposition is very low, such as that exhibited by the torroidal source PIII reactor of FIG. 85.

The advantage of a low minimum ion implant energy increases the range of junction depths of which the PIII reactor of FIG. 85 is capable (by reducing the lower limit of that range). This advantage is illustrated in the graph of FIG. 102, in which plasma potential is plotted as a function of plasma source power for the torroidal source PIII reactor of FIG. 85 and for the capacitively coupled PIII reactor of FIG. 83A, for the sake of comparison. The plasma potential is the potential on ions at the wafer surface due to the plasma electric field in the absence of any bias voltage on the wafer, and therefore is an indicator of the minimum energy at which ions can be implanted. FIG. 102 shows that the plasma potential increases indefinitely as the source power is increased in the capacitively coupled PIII reactor of FIG. 83A, so that in this reactor the

minimum implant energy is greatly increased (the implant energy/depth range is reduced) at high plasma density or ion implant flux levels. In contrast, above a threshold power PTH, the torroidal source PIII reactor of FIG. 85 exhibits a  
5 very gradual (nearly imperceptible) increase in plasma potential as source power is increased, so that the plasma potential is very low even at high plasma source power or ion density (high ion implant flux). Therefore, the range of plasma ion energy (ion implant depth) is much larger in  
10 the PIII reactor of FIG. 85 because the minimum energy remains very low even at high ion flux levels.

The plasma potential in the capacitively coupled PIII reactor of FIG. 83A can be reduced by increasing the source  
15 power frequency. However, this becomes more difficult as the junction depth and corresponding ion energy is reduced. For example, to reach a plasma potential that is less than 500 eV (for a 0.5 kV Boron implant energy), the source power frequency would need to be increased well into the VHF range  
20 and possibly above the VHF range. In contrast, the source power frequency of the torroidal source PIII reactor of FIG. 85 can be in the HF range (e.g., 13 MHz) while providing a low plasma potential.

25 A further advantage of the torroidal source PIII reactor of FIG. 85 over the capacitively coupled source PIII reactor of FIG. 83A is that the torroidal source PIII reactor has a thinner plasma sheath in which proportionately fewer inelastic collisions of ions occur that tend to skew  
30 the ion implant energy distribution. This thinner sheath may be nearly collisionless. In contrast, the capacitively coupled source PIII reactor of FIG. 83A generates plasma ions in the sheath by an HF or VHF RF source that tends to produce a much thicker sheath. The thicker sheath produces  
35 far more collisions that significantly skew ion energy distribution. The result is that the ion implanted junction

profile is far less abrupt. This problem is more acute at lower ion energies (shallower implanted junctions) where the skew in energy produced by the collisions in the thicker sheath represent a far greater fraction of the total ion energy. The torroidal source PIII reactor of FIG. 85 therefore has more precise control over ion implant energy and is capable of producing implanted junctions with greater abruptness, particularly for the more shallow junctions that are needed for the more advanced (smaller feature size) technologies.

A related advantage of the torroidal source PIII reactor of FIG. 85 is that it can be operated at much lower chamber pressures than the capacitively coupled PIII reactor of FIG. 83A. The capacitively coupled PIII reactor of FIG. 83A requires a thicker sheath to generate plasma ions in the sheath, which in turn requires higher chamber pressures (e.g., 10-100 mT). The torroidal source PIII reactor of FIG. 85 does not need to generate plasma near the sheath with bias power and for many applications therefore is best operated with a thinner (nearly collisionless) sheath, so that chamber pressures can be very low (e.g., 1-3 mT). This has the advantage of a wider ion implantation process window in the torroidal source PIII reactor. However, as will be discussed with reference to doping of a three dimensional structure such as a polysilicon gate having both a top surface and vertical side walls, velocity scattering of dopant ions in the sheath enables ions to implant not only the top surface of the polysilicon gate but also implant its side walls. Such a process may be referred to as conformal ion implanting. Conformal ion implanting has the advantage of doping the gate more isotropically and reducing carrier depletion at the gate-to-thin oxide interface, as will be discussed below. Therefore, some sheath thickness is desirable in order to scatter a fraction of the dopant ions away from a purely vertical trajectory so that the scattered

fraction implants into the side walls of the polysilicon gate. (In contrast, in an ion beam implanter, such scattering is not a feature, so that only the gate top surface is implanted.) Another advantage of a plasma sheath of finite thickness (and therefore finite collisional cross-section) is that some very slight scattering of all the ions from a purely vertical trajectory (i.e., a deflection of only a few degrees) may be desirable in some cases to avoid implanting along an axis of the wafer crystal, which could lead to channeling or an implant that is too deep or a less abrupt junction profile. Also, scattering of the ions leads to placement of dopants under the polysilicon gate. This can be very useful in optimizing CMOS device performance by controlling the dopant overlap under the poly Si gate and Source drain extension areas, as will be discussed later in this specification in more detail.

The low contamination exhibited by the torroidal source PIII reactor of FIG. 85 is due primarily to the tendency of the plasma to not interact with chamber surfaces and instead oscillate or circulate in the torroidal paths that are generally parallel to the chamber surfaces rather than being towards those surfaces. Specifically, the pair torroidal paths followed by the plasma current are parallel to the surfaces of the respect reentrant conduits 8150, 8151 of FIG. 85 and parallel to the interior surface of the ceiling 8015 and of the wafer support pedestal 8025. In contrast, the plasma source power generates electric fields within the capacitively coupled PIII reactor of FIG. 83A that are oriented directly toward the ceiling and toward the chamber walls.

In the torroidal source PIII reactor of FIG. 85, the only significant electric field oriented directly toward a chamber surface is produced by the bias voltage applied to the wafer support pedestal 8025, but this electric field

does not significantly generate plasma in the embodiment of FIG. 85. While the bias voltage can be a D.C. (or pulsed D.C.) bias voltage, in the embodiment of FIG. 85 the bias voltage is an RF voltage. The frequency of the RF bias voltage can be sufficiently low so that the plasma sheath at the wafer surface does not participate significantly in plasma generation. Thus, plasma generation in the torroidal source PIII reactor of FIG. 85 produces only plasma currents that are generally parallel to the interior chamber surfaces, and thus less likely to interact with chamber surfaces and produce contamination.

Further reduction of metal contamination of ion implantation processes is achieved by first depositing a passivation layer on all chamber surfaces prior to performing the ion implantation process. The passivation layer may be a silicon-containing layer such as silicon dioxide, silicon nitride, silicon, silicon carbide, silicon hydride, silicon fluoride, boron or phosphorous or arsenic doped silicon, boron or phosphorous or arsenic doped silicon carbide, boron or phosphorous or arsenic doped silicon oxide. Alternatively, the passivation may be a fluorocarbon or hydrocarbon or hydrofluorocarbon film. Compounds of germanium may also be used for passivation. Alternatively, the passivation layer may be a dopant-containing layer such as boron, phosphorous, arsenic or antimony formed by decomposition of a compound of the dopant precursor gas, such as  $\text{BF}_3$ ,  $\text{B}_2\text{H}_6$ ,  $\text{PF}_3$ ,  $\text{PF}_5$ ,  $\text{PH}_3$ ,  $\text{AsF}_3$ , or  $\text{AsH}_3$ . It may be advantageous to form a passivation layer with a source gas or source gas mixture using gas(es) similar to that or those that are to be used in the subsequent plasma immersion implantation process step. (This may reduce unwanted etching of the passivation layer by the subsequent implant process step.) Alternatively, it may be advantageous to combine the fluoride and the hydride of a particular gas to minimize the fluorine and/or hydrogen incorporated in the passivation



layer, for example,  $\text{BF}_3+\text{B}_2\text{H}_6$ ,  $\text{PH}_3+\text{PF}_3$ ,  $\text{AsF}_3+\text{AsH}_3$ ,  $\text{SiF}_4+\text{SiH}_4$ , or  $\text{GeF}_4+\text{GeH}_4$ .

While the RF bias frequency of the torroidal source  
5 PIII reactor of FIG. 85 is sufficiently low to not affect  
plasma generation by the plasma source power applicators  
8110, 8111, it is also sufficiently low to permit the ions  
in the plasma sheath to follow the sheath oscillations and  
thereby acquire a kinetic energy of up to the equivalent to  
10 the full peak-to-peak voltage of the RF bias power applied  
to the sheath, depending upon pressure and sheath thickness.  
This reduces the amount of RF bias power required to produce  
a particular ion energy or implant depth. On the other  
hand, the RF bias frequency is sufficiently high to avoid  
15 significant voltage drops across dielectric layers on the  
wafer support pedestal 8025, on chamber interior walls and  
on the wafer itself. This is particularly important in ion  
implantation of very shallow junctions, in which the RF bias  
voltage is correspondingly small, such as about 150 volts  
20 for a 100 Angstrom junction depth (for example). An RF  
voltage drop of 50 volts out of a total of 150 volts across  
the sheath (for example) would be unacceptable, as this  
would be a third of the total sheath voltage. The RF bias  
frequency is therefore sufficiently high to reduce the  
25 capacitive reactance across dielectric layers so as to limit  
the voltage drop across such a layer to less than on the  
order of 10% of the total RF bias voltage. A frequency  
sufficiently high meet this latter requirement while being  
sufficiently low for the ions to follow the sheath  
30 oscillations is in the range of 100 kHz to 10 MHz, and more  
optimally in the range of 500 kHz to 5 MHz, and most  
optimally about 2 MHz. One advantage of reducing capacitive  
voltage drops across the wafer pedestal is that the sheath  
voltage can be more accurately estimated from the voltage  
35 applied to the pedestal. Such capacitive voltage drops can  
be across dielectric layers on the front or back of the

wafer, on the top of the wafer pedestal and (in the case of an electrostatic chuck) the dielectric layer at the top of the chuck.

5        Ion implantation results produced by the torroidal source PIII reactor of FIG. 85 compare favorably with those obtained with a conventional beam implanter operated in drift mode, which is much slower than the PIII reactor. Referring to FIG. 103, the curves "A" and "a" are plots of  
10       dopant (boron) volume concentration in the wafer crystal as a function of depth for boron equivalent energies of 0.5 keV. (As will be discussed below, to achieve the same ion energy as the beam implanter, the bias voltage in the PIII reactor must be twice the acceleration voltage of the beam  
15       implanter.) Even though the PIII reactor (curve "A") is four times faster than the beam implanter (curve "B"), the implant profile is nearly the same, with the same junction abruptness of about 3 nanometers (change in junction depth) per decade (of dopant volume concentration) and junction  
20       depth (about 100 Angstroms). Curves "B" and "b" compare the PIII reactor results ("B") with those of a conventional beam implanter ("b") at boron equivalent energies of 2 keV, showing that the junction abruptness and the junction depth (about 300 Angstroms) is the same in both cases. Curves  
25       "C" and "c" compare the PIII reactor results ("C") with those of a conventional beam implanter ("c") at boron equivalent energies of 3.5 keV, showing that the junction depth (about 500 Angstroms) is the same in both cases.

30       FIG. 103 compares the PIII reactor performance with the conventional beam implanter operated in drift mode (in which the beam voltage corresponds to the desired junction depth). Drift mode is very slow because the beam flux is low at such low beam energies. This can be addressed by using a much  
35       higher beam voltage and then decelerating the beam down to the correct energy before it impacts the wafer. The

deceleration process is not complete, and therefore leaves an energy "contamination" tail (curve "A" of FIG., 104) which can be reduced by rapid thermal annealing to a better implant profile with greater abruptness (curve "B" of FIG. 104). Greater activated implanted dopant concentration, however, can be achieved using a dynamic surface annealing process employing localized melting or nearly melting temperatures for very short durations. The dynamic surface annealing process does not reduce energy contamination tails, such as the energy contamination tail of curve "C" of FIG. 105. In comparison, the torroidal source PIII reactor of FIG. 85 needs no deceleration process since the bias voltage corresponds to the desired implant depth, and therefore has no energy contamination tail (curve "D" of FIG. 105). Therefore, the PIII reactor can be used with the dynamic surface anneal process to form very abrupt ultra shallow junction profile, while the conventional beam implanter operating in deceleration mode cannot. The dynamic surface annealing process consists of locally heating regions of the wafer surface to nearly (e.g., within 100 to 50 degrees of) its melting temperature for very short durations (e.g., nano-seconds to tens of milliseconds) by scanning a laser beam or a group of laser beams across the wafer surface.

25

FIG. 106 illustrates how much greater a dopant concentration can be attained with the dynamic surface annealing process. Curve "A" of FIG. 106 illustrates the wafer resistivity in Ohms per square as a function of junction depth using a beam implanter and a rapid thermal anneal of the wafer at 1050 degrees C. The concentration of dopant reached  $10E20$  per cubic centimeter. Curve "B" of FIG. 106 illustrates the wafer resistivity in Ohms per square as a function of junction depth using the torroidal source PIII reactor of FIG. 85 and a dynamic surface anneal process after implanting at a temperature of 1300 degrees C.

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The concentration of the dopant reached  $5 \times 10^{20}$  following the dynamic surface annealing, or about five times that achieved with rapid thermal annealing. FIG. 107 illustrates how little the implanted dopant profile changes during dynamic surface annealing. Curve "A" of FIG. 107 is the dopant distribution prior to annealing while curve "B" of FIG. 107 is the dopant distribution after annealing. The dynamic surface annealing process causes the dopant to diffuse less than 10 Å, while it does not adversely affect the junction abruptness, which is less than 3.5 nm/decade. This tendency of the dynamic surface annealing process to minimize dopant diffusion facilitates the formation of extremely shallow junctions. More shallow junctions are required (as source-to-drain channel lengths are decreased in higher speed devices) in order to avoid source-to-drain leakage currents. On the other hand, the shallower junction require much higher active dopant concentrations (to avoid increased resistance) that can best be realized with dynamic surface annealing. As discussed elsewhere in this specification, junction depth can be reduced by carrying out a wafer amorphization step in which the wafer is bombarded with ions (such as silicon or germanium ions) to create lattice defects in the semiconductor crystal of the wafer. We have implanted and annealed junctions having a high dopant concentration corresponding to a low resistivity (500 Ohms per square), an extremely shallow junction depth (185 Å) and a very steep abruptness (less than 4nm/decade). In some cases, the depth of the amorphizing or ion bombardment process may extend below the dopant implant junction depth. For example, amorphization using SiF<sub>4</sub> gas and a 10 kV peak-to-peak bias voltage in the PIII reactor of FIG. 85 forms an amorphized layer to a depth of about 150 Angstroms, while dopant (boron) ions accelerated across a 1000 peak-to-peak volt sheath (bias) voltage implant to a depth of only about 100 Angstroms.

FIG. 108 illustrates the bias voltage for the torroidal source PIII reactor (left hand ordinate) and the beam voltage for the ion beam implanter (right hand ordinate) as a function of junction depth. The PIII reactor and the beam implanter produce virtually identical results provided the PIII reactor bias voltage is twice the beam voltage.

#### Working Examples:

10 A principal application of a PIII reactor is the formation of PN junctions in semiconductor crystals. FIGS. 109 and 110 illustrate different stages in the deposition of dopant impurities in the fabrication of a P-channel metal oxide semiconductor field effect transistor (MOSFET).

15 Referring first to FIG. 109, a region 9960 of a semiconductor (e.g., silicon) wafer may be doped with an N-type conductivity impurity, such as arsenic or phosphorus, the region 9960 being labeled "n" in the drawing of FIG. 109 to denote its conductivity type. A very thin silicon

20 dioxide layer 9962 is deposited on the surface of the wafer including over n-type region 9960. A polycrystalline silicon gate 9964 is formed over the thin oxide layer 9962 from a blanket polysilicon layer that has been doped with boron in the PIII reactor. After formation of the gate

25 9964, p-type dopant is implanted in the PIII reactor to form source and drain extensions 9972 and 9973. Spacer layers 9966 of a dielectric material such as silicon dioxide and/or silicon nitride (for example) are formed along two opposite vertical sides 9964a, 9964b of the gate 9964. Using the

30 PIII reactor of FIG. 85 with a process gas consisting of  $\text{BF}_3$  or  $\text{B}_2\text{H}_6$  (for example), boron is implanted over the entire N-type region 9960. The spacer layers mask their underlying regions from the boron, so that P-type conductivity source and drain contact regions 9968, 9969 are formed on either

35 side of the gate 9964, as shown in FIG. 110. This step is carried out with a boron-containing species energy in the

range of 2 to 10 kVpp on the RF bias voltage (controlled by the RF bias power generator 8065 of FIG. 85). In accordance with the example of FIG. 108, the RF bias voltage on the wafer pedestal 8025 in the PIII reactor of FIG. 85 is twice  
5 the desired boron energy. The implantation is carried out for a sufficient time and at a sufficient ion flux or ion density (controlled by the RF source power generators 8055, 8056 of FIG. 85) to achieve a surface concentration of boron exceeding  $5 \times 10^{15}$  atoms per square centimeter. The  
10 concentration of boron in the gate 9964 is then increased to  $1 \times 10^{16}$  atoms per square centimeter by masking the source and drain contacts 9968, 9969 (by depositing a layer of photoresist thereover, for example) and carrying out a further (supplementary) implantation step of boron until the  
15 concentration of boron in the gate 9964 reaches the desired level ( $1 \times 10^{16}$  atoms/cubic centimeter). The source and drain contacts 9968, 9969 are not raised to the higher dopant concentration (as is the gate 9964) because the higher dopant concentration may be incompatible with  
20 formation of a metal silicide layer (during a later step) over each contact 9968, 9969. However, the gate 9964 must be raised to this higher dopant concentration level in order to reduce carrier depletion in the gate 9964 near the interface between the gate 9964 and the thin silicon dioxide  
25 layer 9962. Such carrier depletion in the gate would impede the switching speed of the transistor. The dopant profile in the gate must be highly abrupt in order attain a high dopant concentration in the gate 9964 near the thin oxide layer 9962 without implanting dopant into the underlying  
30 thin oxide layer 9962 or into the source-to-drain channel underlying the thin oxide layer 9962. Another measure that can be taken to further enhance gate performance and device speed is to raise the dielectric constant of the thin silicon dioxide layer 9962 by implanting nitrogen in the  
35 thin silicon dioxide layer 9962 so that (upon annealing) nitrogen atoms replace oxygen atoms in the layer 9962, as

will be described later in this specification. A further measure for enhancing gate performance is conformal implanting in which dopant ions that have been deflected from their vertical trajectory by collisions in the plasma sheath over the wafer surface are able to implant into the vertical side walls of the gate 9964. This further increases the dopant concentration in the gate 9964 near the interface with the thin oxide layer 9962, and provide a more uniform and isotropic dopant distribution within the gate.

A yet further measure for enhancing gate performance for gates of N-channel devices implanted with arsenic is to implant phosphorus during the supplementary implant step using the PIII reactor. The phosphorus is lighter than arsenic and so diffuses more readily throughout the semiconductor crystal, to provide less abrupt junction profile in the source drain contact areas.

The depth of the ion implantation of the source and drain contacts 9968, 9969 may be in the range of 400 to 800 Å. If the gate 9964 is thinner than that, then the gate 9964 must be implanted in a separate implantation step to a lesser depth to avoid implanting any dopant in the thin oxide layer 9962 below the gate 9964. In order to avoid depletion in the region of the gate 9964 adjacent the thin oxide layer 9962, the implantation of the gate must extend as close to the gate/oxide interface as possible without entering the thin oxide layer 9962. Therefore, the implant profile of the gate must have the highest possible abruptness (e.g., 3 nm/decade or less) and a higher dopant dose (i.e.,  $1 \times 10^{16}$  atoms/cm<sup>2</sup> ).

Referring now to FIG. 110, source and drain extensions 9972, 9973 are typically formed before depositing and forming the spacer layers 9966 of FIG. 109. The extensions layers are formed by carrying out a more shallow and light implant of boron over the entire region 9960. Typically,

the junction depth of the source and drain extensions is only about 100 to 300 Angstroms and the implant dose is less than  $5 \times 10^{15}$  atoms/square centimeter. This implant step, therefore, has little effect on the dopant profiles in the  
5 gate 9964 or in the source and drain contacts 9968, 9969, so that these areas need not be masked during the implantation of the source and drain extensions 9972, 9973. However, if masking is desired, then it may be carried out with photoresist. The source and drain extensions are implanted  
10 at an equivalent boron energy of 0.5 kV, requiring a 1.0 kVpp RF bias voltage on the wafer pedestal 8025 of FIG. 85.

The same structures illustrated in FIGS. 109 and 110 are formed in the fabrication of an N-channel MOSFET.  
15 However, the region 9960 is initially doped with a P-type conductivity such as boron and is therefore a P-type conductivity region. And, the implantation of the gate 9964 and of the source and drain contacts 9968, 9969 (illustrated in FIG. 109) is carried out in a beam implanter (rather than  
20 in a PIII reactor) with an N-type conductivity impurity dopant such as arsenic. Furthermore, the supplementary implantation of the gate 9964 that raises its dopant dose concentration to  $1 \times 10^{16}$  atoms/cm<sup>2</sup> is carried out in the PIII reactor with phosphorus (rather than arsenic) using a  
25 phosphorus-containing process gas. Phosphorus is preferred for this latter implantation step because it diffuses more uniformly than arsenic, and therefore enhances the quality of the N-type dopant profile in the gates 9964 of the N-channel devices. The ion beam voltage is in the range of  
30 15-30 kV for the arsenic implant step (simultaneous implanting of the N-channel source and drain contacts 9968, 9969 and of the N-channel gates 9964), and is applied for a sufficient time to reach a dopant surface concentration exceeding  $5 \times 10^{15}$  atoms per cubic centimeter. The  
35 supplementary gate implant of phosphorus is carried out at an ion beam voltage in the range of only 2-5 kV for a



sufficient time to raise the dopant surface concentration in the N-channel gates to  $1 \times 10^{16}$  atoms/cubic cm.

5       The implantation steps involving phosphorus and boron are advantageously carried out in the PIII reactor rather than an ion beam implanter because the ion energies of these light elements are so low that ion flux in a beam implanter would be very low and the implant times would be inordinately high (e.g., half an hour per wafer). In the  
10   PIII reactor, the source power can be 800 Watts at 13.56 MHz (with the 200 kHz offset between the two torroidal plasma currents as described above), the implant step being carried out for only 5 to 40 seconds per wafer.

15       The sequence of ion implantation steps depicted in FIGS. 109 and 110 may be modified, in that the light shallow source and drain extension implant step of FIG. 110 may be carried out before or after formation of the spacer layer 9966 and subsequent heavy implantation of the contacts 9968,  
20   9969 and gate 9964. When extension implants are done after the spacer layer 9966 is formed, the spacer layer 9966 must be removed before the extension implants are performed.

      One example of a process for fabricating complementary  
25   MOSFETS (CMOS FETs) is illustrated in FIG. 111. In the first step (block 9980), the P-well and N-well regions of the CMOS device are implanted in separate steps. Then, a blanket thin gate oxide layer and an overlying blanket polysilicon gate layer are formed over the entire wafer  
30   (block 9981 of FIG. 111). The P-well regions are masked and the N-well regions are left exposed (block 9982). The portions of the polysilicon gate layer lying in the N-well regions are then implanted with boron in a PIII reactor (block 9983). The P-channel gates (9964 in FIG. 109) are  
35   then photolithographically defined and etched, to expose portions of the silicon wafer (block 9984). Source and

drain extensions 9972, 9973 of FIG. 109 self-aligned with the gate 9964 are then formed by ion implantation of boron using the PIII reactor (block 9985). A so-called "halo" implant step is then performed to implant an N-type dopant under the edges of each P-channel gate 9964 (block 9986). This is done by implanting arsenic using an ion beam tilted at about 30 degrees from a vertical direction relative to the wafer surface and rotating the wafer. Alternatively, this step may be accomplished by implanting phosphorus in the PIII reactor using a chamber pressure and bias voltage conducive to a large sheath thickness to promote collisions in the sheath that divert the boron ions from a vertical trajectory. Then, the spacer layers 9986 are formed over the source drain extensions 9972, 9973 (block 9987) and boron is then implanted at a higher energy to form the deep source drain contacts 9969 (block 9988), resulting in the structure of FIG. 110. The reverse of step 9982 is then performed by masking the N-well regions (i.e., the P-channel devices) and exposing the P-well regions (block 9992). Thereafter steps 9993 through 9998 are performed that correspond to steps 9983 through 9988 that have already been described, except that they are carried out in the P-well regions rather than in the N-well regions, the dopant is Arsenic rather than Boron, and a beam line ion implanter is employed rather than a PIII reactor. And, for the N-channel device halo implant of block 9996 (corresponding to the P-channel device halo implant of block 9986 described above), the dopant is a P-type dopant such as boron. In the case of the N-channel devices implanted in steps 9993 through 9998, a further implant step is performed, namely a supplemental implant step (block 9999) to increase the dose in the polysilicon gate as discussed above in this specification. In the supplemental implantation step of block 9999, phosphorus is the N-type dopant impurity and is implanted using a PIII reactor rather than a beam implanter (although a beam implanter could be employed instead).

As noted above, the process may be reversed so that the gate 9964 and source and drain contacts 9968, 9969 are implanted before the source and drain extensions 9972, 9973.

5

After all ion implantations have been carried out, the wafer is subjected to an annealing process such as spike annealing using rapid thermal processing (RTP) and/or the dynamic surface annealing (DSA) process discussed earlier in this specification. Such an annealing process causes the implanted dopant ions, most of which came to rest in interstitial locations in the crystal lattice, to move to atomic sites, i.e., be substituted for silicon atoms originally occupying those sites. More than one annealing step can be used to form the pmos and nmos devices and these steps can be inserted in the process flow as appropriate from activation and diffusion point of view.

The foregoing ion implantation processes involving the lighter atomic elements (e.g., boron and phosphorus) are carried out using a PIII reactor in the modes described previously. For example, the bias power frequency is selected to maximize ion energy while simultaneously providing low impedance coupling across dielectric layers. How this is accomplished is described above in this specification.

The ion implantation processes described above are enhanced by other processes. Specifically, in order to prevent channeling and in order to enhance the fraction of implanted ions that become substitutional upon annealing, the semiconductor wafer crystal may be subjected to an ion bombardment process that partially amorphizes the crystal by creating crystal defects. The ions employed should be compatible with the wafer material, and may be formed in the PIII reactor in a plasma generated from one or more of the

following gases: silicon fluoride, silicon hydride, germanium fluoride, germanium hydride, Xenon, Argon, or carbon fluoride (ie. tetrafluoromethane, octafluorocyclobutane, etc) or carbon hydride (ie. methane, acetylene, etc) or carbon hydride/fluoride (ie. tetrafluoroethane, difluoroethylene, etc) gases. One advantage of the PIII reactor is that its implant processes are not mass selective (unlike an ion beam implanter). Therefore, during ion implantation of a dopant impurity such as boron, any other element may also be implanted simultaneously, regardless of ion mass in the PIII reactor. Therefore, unlike an ion beam implanter, the PIII reactor is capable of simultaneously implanting a dopant impurity while carrying out an amorphizing process. This may be accomplished using a  $\text{BF}_3$  gas (to provide the dopant ions) mixed with an  $\text{SiF}_4$  gas (to provide the amorphizing bombardment ion species). Such a simultaneous ion implantation process is referred to as a co-implant process. The amorphization process may also be carried out sequentially with the doping process. In addition to amorphization, simultaneous implants of dopant and non-dopant atoms such as Fluorine, Germanium, Carbon or other elements are done to change the chemistry of the Silicon wafer. This change in chemistry can help in increasing dopant activation and reducing dopant diffusion.

Another process that can be carried out in the PIII reactor is a surface enhancement process in which certain ions are implanted in order to replace other elements in the crystal. One example of such a surface enhancement process is nitrodization. In this process, the dielectric constant of the thin silicon dioxide layer 9962 is increased (in order to increase device speed) by replacing a significant fraction of the oxygen atoms in the silicon dioxide film with nitrogen atoms. This is accomplished in the PIII reactor by generating a plasma from a nitrogen-containing

gas, such as ammonia, and implanting the nitrogen atoms into the silicon dioxide layer 9962. This step may be performed at any time, including before, during and/or after the implantation of the dopant impurity species. If the  
5 nitrodization process is performed at least partially simultaneously with the dopant ion implant step, then the nitrodization process is a co-implant process. Since the ion implantation process of the PIII reactor is not mass selective, the co-implant process may be carried out with  
10 any suitable species without requiring that its atomic weight be the same as or related to the atomic weight of the dopant implant species. Thus, for example, the dopant species, boron, and the surface enhancement species, nitrogen, have quite different atomic weights, and yet they are implanted  
15 simultaneously in the PIII reactor. Typically nitrodization is performed without implanting dopant atoms.

A further process related to ion implantation is surface passivation. In this process, the interior surfaces  
20 of the reactor chamber, including the walls and ceiling, are coated with a silicon-containing passivation material (such as silicon dioxide or silicon nitride or silicon hydride) prior to the introduction of a production wafer. The passivation layer prevents the plasma from interacting with  
25 or sputtering any metal surfaces within the plasma reactor. The deposition of the passivation layer is carried out by igniting a plasma within the reactor from a silicon containing gas such as silane mixed with oxygen, for example. This passivation step, combined with the low-  
30 contamination toroidal source PIII reactor of FIG. 85, has yielded extremely low metal contamination of a silicon wafer during ion implantation, about 100 times lower than that typically obtained in a conventional beam implanter.

35 Upon completion of the ion implantation process, the passivation layer is removed, using a suitable etchant gas

such as NF<sub>3</sub> which may be combined with a suitable ion bombardment gas source such as argon oxygen, or hydrogen. During this cleaning step, the chamber surfaces may be heated to 60 degrees C or higher to enhance the cleaning process. A new passivation layer is deposited before the next ion implantation step.

Alternatively, a new passivation layer may be deposited before implanting a sequence of wafers, and following the processing of the sequence, the passivation layer and other depositions may be removed using a cleaning gas.

FIG. 112 is a flow diagram showing the different options of combining the foregoing ion implantation-related processes with the dopant implantation processes of FIG. 111. A first step is cleaning the chamber to remove contamination or to remove a previously deposited passivation layer (block 9001 of FIG. 112). Next, a passivation layer of silicon dioxide, for example, is deposited over the interior surfaces of the chamber (block 9002) prior to the introduction of the wafer to be processed. Next, the wafer is introduced into the PIII reactor chamber and may be subjected to a cleaning or etching process to remove thin oxidation layers that may have accumulated on the exposed semiconductor surfaces in the brief interim since the wafer was last processed (block 9003). A pre-implant wafer amorphizing process may be carried out (block 9004) by ion-bombarding exposed surfaces of the wafer with silicon ions, for example. A pre-implant surface enhancement process may also be carried out (block 9005) by implanting a species such as nitrogen into silicon dioxide films. The dopant implantation process may then be carried out (block 9006). This step is an individual one of the boron or phosphorus implant steps illustrated in the general process flow diagram of FIG. 111. During the dopant implant process of block 9006, other ions in addition to the

dopant ions may be implanted simultaneously in a co-implant process (block 9007). Such a co-implant process (9007) may be an amorphizing process, a light etch process that prevents accumulation of plasma by-products on the wafer surface, enhancing dopant activation and reducing dopant diffusion, or surface enhancement process. After completion of the dopant ion implant process (9006) and any co-implant process (9007), various post implant processes may be carried out. Such post implant processes may include a surface enhancement process (block 9008). Upon completion of all implant steps (including the step of block 9008), an implant anneal process is carried out (block 9012) after removing any photo-resist mask layers on the wafer in the preceding wafer clean step of block 9009. This anneal process can be a dynamic surface anneal in which a laser beam (or several laser beams) are scanned across the wafer surface to locally heat the surface to nearly melting temperature (about 1300 degrees C) or to melting temperature, each local area being heated for an extremely short period of time (e.g., on the order of nanoseconds to tens of milliseconds ). Other post implant processes carried out after the anneal step of block 9112 may include a wafer cleaning process (block 9009) to remove layers of plasma by-products deposited during the ion implantation process, deposition of a temporary passivation coating on the wafer to stabilize the wafer surface (block 9010) and a chamber cleaning process (block 9011), carried out after removal of the wafer from the PIII reactor chamber, for removing a previously deposited passivation layer from the chamber interior surfaces.

While the invention has been described in detail by specific reference to preferred embodiments, it is understood that variations and modifications thereof may be made without departing from the true spirit and scope of the invention.